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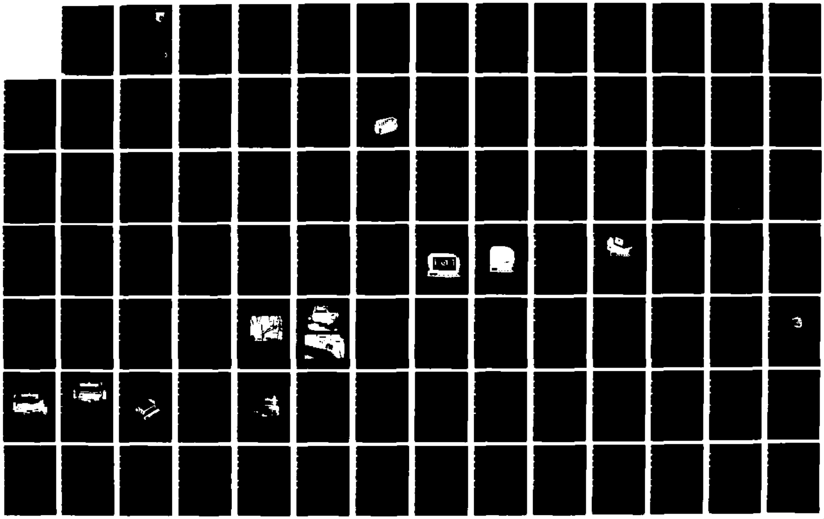

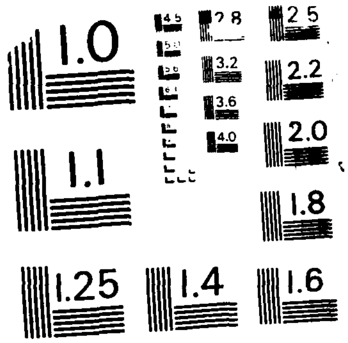

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ADVANCED CAPACITOR DEVELOPMENT

Robert S. Buritz

Hughes Aircraft Company
Post Office Box 902
El Segundo, CA 90245

November 1986

Interim Report for Period October 1984 — April 1986

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AEROPROPULSION LABORATORY
Air Force Wright Aeronautical Laboratories
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433-6563

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This technical report has been reviewed and is approved for publication.

PETER T. LAMM, Project Engineer
Power Components Branch
Aerospace Power Division
Aero Propulsion Laboratory

PAUL R. BERTHEAUD, Chief
Power Components Branch
Aerospace Power Division
Aero Propulsion Laboratory

WILLIAM A. SEWARD, Major, USAF
Deputy Director
Aerospace Power Division
Aero Propulsion Laboratory

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ABSTRACT

This interim report describes the technical approach taken by the Hughes Aircraft Company for the development and testing of airborne ac filter capacitors that will operate at ambient temperatures exceeding 200°C. To meet the goals of this program, a new capacitor was designed. This design manages the thermal problem. The internal dielectric heat is conducted efficiently to the outside. The hot-spot temperature is less than the upper limit of the dielectric material when the ambient temperature is 200°C.

Three candidate materials with suitable properties were investigated, Kapton type H, mica paper, and Teflon. Unfortunately, Teflon cold flows, and hence was considered unsuitable. Mica paper could not be used unimpregnated. Kapton film was felt to be adequate to meet the goals of this program. Its operating temperature will be limited by its dissipation factor to about 230°C.

The proposed design is for single capacitor pad made up of alternate sheets of Kapton and aluminum foil. The 45 uF capacitor design is based on using 0.3 mil Kapton, 3-3/4 inches wide, with aluminum foil 0.17 mil by 3-1/2 inches wide. The number of layers required is 2155. The overall case dimensions are 5.9 × 5.4 × 3.4 inches. The 180 uF capacitor design is similar to the 45 uF capacitor design, but larger. The design is based on Kapton, 4-1/2 inches wide. The number of layers required is 5870. The overall case dimensions are 6.6 × 6.1 × 5.5 inches.

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The equipment for cutting the Kapton and foil sheets comprises three separate units, one for the Kapton and two for the aluminum foils. Each unit consists of a roll of aluminum or Kapton material and a large rubber covered supply roll. When the supply roll is rotated, it pulls the film or foil from the reel. Stops control the amount of material dispensed. The material is then cutoff with shears and conveyed to the stacking fixture. The three units are interlocked and counters provide the total number of layers.

Six experimental pads were made to develop the procedures and processes needed. The first two pads assembled consisted of 500 layers each of 0.5 mil Kapton and aluminum foil. The remaining pads were made with 0.3 mil Kapton. All the units exhibited breakdown at less than 400 Vdc. Failure analyses indicated that the cause of the breakdowns were aluminum fragments from the cutting operation. Substituting hard temper foil for annealed aluminum and tearing the foil rather than shearing it eliminated these fragments. S/N 2 was heated in a vacuum oven to 203°C for 4 hours successfully.

Much was learned during assembly of the six experimental pads. The film cutting apparatus was developed successfully. A new method of cutting the aluminum foil replaced the shears. A test fixture was developed for compressing and testing the pad during assembly. At this point assembly of the prototype pads was begun.

The first prototype pad (S/N 7) consisted of 1300 layers of 0.3 mil Kapton 3-3/4 inch wide. The capacitance was 23.6 uF and the dissipation factor 0.016. The pad was heated in a vacuum oven at 200°C for 115 hours. After recompressing the stack and correcting faulty line terminations, the capacitance was 25.9 uF and the dissipation factor was 0.001.

During assembly the stack was tested frequently. Numerous shorts were attributed to particles in the foil rolls and to the Kapton film quality. Therefore, it was decided to use heavier Kapton for the remaining capacitors.

The construction of S/N 8 was identical to S/N 7 except that 0.5 mil Kapton was used instead kof 0.3 mil. Foil or film that showed any evidence of particles or irregularities was not used. The pad was tested every 100 layers; no shorts were found. The number of layers required for 45 uF was estimated and stacking terminated at 3500 layers. After the terminations are completed the capacitor will be tested.

A capacitor test plan was prepared to provide the test procedures; it describes the performance tests to be performed for both types of capacitors. These tests will establish the electrical characteristics of the capacitors. Burn-in tests and life tests at 200°C will demonstrate that the design is suitable for high temperature operation.

The work remaining is to make additional prototype capacitors and to carry out the Phase III performance tests.

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FOREWORD

This interim report presents the progress made by Hughes Aircraft Company in developing and testing advanced capacitors under Contract F33615-84-C-2424, supported by the Air Force Wright Aeronautical Laboratories, Aero Propulsion Laboratory at Wright-Patterson Air Force Base, Ohio. Capt. Neal Harold monitored the program from its inception. Robert S. Buritz is the program manager.

This part of the program (Phase I) was conducted by Hughes Aircraft Company at its El Segundo, California facility.

Ernest R. Haberland designed the capacitors, including the fabricating equipment. William C. Kainsinger assisted Mr. Haberland. James K. Bell made the drawings. Shigeo Kusunoki made the capacitor fabricating equipment and hardware. Teresa J. Parks and Luke M. Flaherty fabricated capacitors.

Haskel M. Joseph provided valuable advice and consultation. Thermal analyses were performed by Peter F. Taylor. Donald C. Smith consulted on high temperature dielectric liquids. Orval F. Buck conducted the contamination analyses.

Many helpful suggestions were provided by Donald L. Stevenson and Greg Wilkenson of Du Pont and Robert J. Purvis of Corona Films, Inc. The advice and consultation of James Huggard and Jeffery D. Lasher of Enka, and Steven Simpson of National Aluminum were very valuable.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF TABLES

I. INTRODUCTION

This document describes the technical approach taken by Hughes Aircraft Company for the development and testing of ac filter capacitors for airborne applications which will have a higher operating temperature than presently available. Successful completion of this program will result in improved lightweight, highly reliable filter capacitors that will operate at ambient temperatures exceeding 200°C. By providing capacitors that will operate in a higher temperature environment the study will significantly advance the state of the art in capacitor technology.

TECHNICAL INTRODUCTION

Two problems faced in achieving higher operating temperatures are the temperature limitation of the dielectric materials and thermal management of the heat generated. Failures are usually caused by the dissipation of relatively large amounts of power in a poorly cooled volume. These failures can take the form of thermal runaway, insulation failure because of very great local hot-spot temperatures, and excessive thermal expansion.

Because the thermal properties of films available for capacitor use range from about 115°C to more than 450°C, operating temperatures up to 300 to 400°C appear to be feasible. Since these numbers far exceed operating temperatures reported in the literature, the question arises as to the reason for the large difference.

In a previous program conducted by Hughes for the Aero Propulsion Laboratory, a high voltage dc filter capacitor and a low voltage ac filter capacitor were developed successfully. The results show energy densities greater than 100 J/lb for the dc filter capacitor.

The ac filter capacitor was tested at high temperatures with Ultem*, a new material. It was hoped this material could operate at 200°C, and therefore could be applied to the present program. The results, however, showed that both the film and the thermal design were grossly inadequate. A better dielectric film is required to achieve operation at 200°C and, of equal importance, efficient conduction of the heat to the outside of the capacitor. It is believed that the latter requirement is difficult to achieve reliably in a conventionally wound capacitor.

The objective of this program is to develop for airborne applications an ac filter capacitor that will operate reliably at ambient temperatures exceeding 200°C.

PROGRAM SUMMARY

The program was divided into three sequential phases composed of a total of five tasks. This interim report is a description of the developmental effort and testing conducted by Hughes to accomplish Phase I.

A brief summary of the program is given below. The complete statement of work is given in Appendix A with the applicable electrical performance tests (Addendum No. 1) shown in Appendix B.

Phase I, Task I - Materials Development

This task identified the most promising materials. Extensive use was made of Hughes experience in the development and application of new materials, and the design of high reliability high voltage capacitors and magnetic devices for airborne and space applications. The most likely approach was to apply existing capacitor dielectric materials. Modifications of these materials was considered to reduce size and weight. New materials were investigated as appropriate to meet the thermal requirements and reduce size and weight.

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*Registered trademark of General Electric.

Phase I, Task II - Preliminary Design

Designs for the 180 μF and 45 μF capacitors were based on the materials development carried out in Task I. The most promising materials were selected and the dielectric properties and maximum operating temperatures estimated. Designs for both capacitors were submitted to the Air Force for review.

Phase I, Task III - Final Design

Designs for both capacitors will be finalized. Assembly techniques and production methods suitable for a production run were developed.

Phase II, Task I - Capacitor Fabrication

Twenty-five capacitors of each size will be fabricated during this phase. A formal test plan was written describing the performance tests.

Phase III, Task I - Tests

The capacitors will be tested in accordance with the test plan. Failures will be analyzed and documented so that improvements can be made.

Two presentations were made during the design effort. A final presentation will be made at the end of the program.

II. TECHNICAL BACKGROUND

INTRODUCTION

The primary objective of this program is to advance the state-of-the-art of airborne filter capacitors. The result will provide high reliability capacitors which will be reduced in size and weight and operate at more than 200°C. The major design parameters are listed in Table 1.

TABLE 1. CAPACITOR DESIGN REQUIREMENTS

Parameters	Requirements
Capacitance	180 μF and 45 μF
Voltage	150 Vrms max.
Frequency	400 Hz
Terminal current	224 A continuous for 180 μF
	20 A continuous for 45 μF
Operating temperature	-55 to +200°C
Thermal shock	10 cycles min
Random vibration	50 to 2000 Hz
Life	1000 hours at 200°C ambient
Weight goal	3.0 lb and 0.5 lb

This program consists of a logical series of steps which naturally fall into four major tasks. In addition to these four tasks, an analysis will be

made that will give a qualitative numerical prediction of the potential reliability and maintainability of the designed capacitor. These tasks are:

1. Materials development
2. Capacitor design
3. Capacitor fabrication
4. Electrical tests
5. Reliability and maintainability.

The capacitor is intended to operate in supersonic aircraft, which means that the capacitor must operate at high temperatures under severe environmental conditions. Dielectric materials now used such as polysulfone and polycarbonate have operating temperatures of 135°C or less, considerably below the 200°C conditions occurring for new systems. The situation is exacerbated by the dielectric heating within the capacitor. To overcome this problem, higher temperature dielectric materials must be used. In addition a low dissipation factor is desirable to minimize the heat generated inside the capacitor. Efficient thermal design is essential to control the upper temperature of the film.

Another important requirement for aircraft operation is the ability of the capacitor to withstand vibration and shock. This requirement defines the case and the method of mechanically anchoring the capacitor in the case. Aircraft operation also constrains the physical design which will make the internal pressure of the capacitor independent of the external ambient pressure.

CRITICAL PARAMETERS

Since the primary objective of this program is to develop ac filter capacitors capable of operating at 200°C or higher, the dielectric film will play a major role. The achievement of this goal will be determined primarily by the properties of the dielectric film used.

The significant properties of a film which will determine its behavior in a capacitor include:

1. Dielectric constant
2. Density

3. Dissipation factor

4. Temperature limits

The first two properties establish the size and weight. This can be seen easily from Equation 1 for the capacitance of a parallel plate capacitor.

$$C = \frac{0.225Ak}{t} \times 10^{-12} \quad \text{Farads} \tag{1}$$

where,

C = capacitance in Farads

A = area of one plate in square inches

t = dielectric thickness in inches

k = relative dielectric constant

From this relationship it is obvious that the smallest size for a given capacitance is obtained by choosing a thin film that has a large dielectric constant. Unfortunately none of the films which might be suitable can be made as thin as needed. The weight of the capacitor is directly proportional to the film density. The material with the lowest density will provide the lightest device.

The problem of selection becomes more complicated when the last two properties are introduced. The electrical loss represented by the dissipation factor is different for different materials, varying from 0.0001 for Teflon* FEP to 0.002 for Kapton-H* for example. In addition, the dissipation factor may change with temperature. This loss is important in two respects. It appears as heat which, if not dissipated, results in temperature increases which will result in catastrophic failure. The second area of concern is the overall efficiency of the system. The energy requirements for the device, including the losses, must be supplied by the aircraft power source. As the losses increase, a corresponding increase in the power requirements occurs, resulting in lower overall efficiency.

*Registered trademark of E. I. DuPont.

RELATED AF PROGRAMS

Capacitors for Aircraft High Power

In this program conducted by Hughes for the Aero Propulsion Laboratory, lightweight high power pulse discharge capacitors were developed*. The effort resulted in the elimination of manufacturing defects and many material problems. Failures in these capacitors were observed to occur at fields in excess of 5 kV/mil, and to be about equally distributed between wearout due to corona at the foil edge and random dielectric failure. The latter was due to dielectric material flaws, such as pin holes, conducting particle inclusions, variations in thickness, and thermally activated flaws.

Advanced Capacitors

The objective of this Hughes-conducted Aero Propulsion Laboratory program was to reduce the failures caused by random dielectric failure by developing materials of higher quality and better dielectric properties, thus allowing a higher capacitor operating field.** At the outset it was thought that a superior dielectric film could be produced simply by eliminating most of the particulate contamination. Many experiments were conducted to evaluate the effect of filtration on the breakdown properties of polysulfone film. In addition to particulate contamination, however, it was found that dissolved ionic impurities caused breakdown. The remaining problem is to develop a practical technique for removing the impurities.

This program also led to evaluating a new material for use in high energy density capacitors. While many of the same problems of particulate and ionic contamination must be considered for this material, tests have shown some promising results. This new material, a polyetherimide developed by G.E., has a higher temperature capability than other film material except Kapton or

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*"Capacitors for Aircraft High Power," United States Air Force Report AFWAL-TR-80-2037, Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio, January 1980.

**"Advanced Capacitors," United States Air Force Report AFWAL-TR-84-2058, Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio, March 1983.

Teflon. Because it is solution-castable it can be made at any thickness desi ed with a very high film quality. Its electrical properties are very stable with temperature and frequency.

Comparison of Ultem and Polysulfone Film

As part of the above program to evaluate Ultem, a direct comparison with polysulfone film was made. The applicable capacitor assembly was a 120 μF 400 Hz filter capacitor used in aircraft power supplies. The original design for this component used 0.25 mil metallized polysulfone film. Forty-two individual capacitors or pads in parallel made up the total 120 μF assembly; each pad was 2.86 μF, between 0.60 and 0.65 inch in diameter, and approximately 1.2 inch long. The electrical stress in the film was about 825 V/mil.

Terminations were made by flame spraying the ends of the pads and soldering a tinned copper strap across each end. The pads were not impregnated, but the total unit was potted in a flexible material and the case hermetically sealed. The assembled capacitor is shown in Figure 1. Part of the case has been removed to show the arrangement of the pads and terminations.

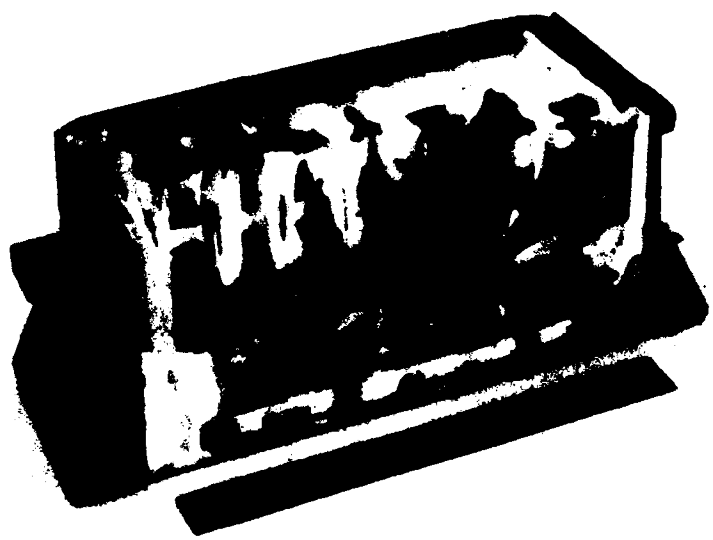

Figure 1. 120 μF filter capacitor showing pad arrangement and interconnections.

The failure mechanisms seen in a sample part were extensive "clearing" at the metallization edge, resulting in low insulation resistance or catastrophic shorting, and similar "clearing" in the bulk of the winding, resulting in reduced insulation resistance. Clearing is localized electrical breakdown of the film and the subsequent self-healing process whereby the metallization vaporizes due to high current density in the region of the short. If incomplete clearing occurs, surface discharges and leakage will cause localized heating and further damage which will spread melting adjacent layers of film. Several causes may contribute to this process. The electrode resistivity has been found to be a major factor, as this will determine the area of metallization which is removed by a given amount of energy passing through the breakdown arc. It has been found that an electrode resistivity of 3 to 4 ohms per square is preferable for the self-healing effect.

The designs for this dielectric were quite simple, consisting of a single layer of metallized film and a space factor which was minimized to whatever extent was possible in the winding process. As shown in Table 2, polysulfone and Ultem films of equal thickness were used in the two designs tested. The pads were wound to capacitance.

TABLE 2. CHARACTERISTICS OF ULTEM AND POLYSULFONE CAPACITOR PADS

Parameters	Polysulfone	Ultem
Capacitance, μF	3.00	3.00
Film thickness, mil	0.24	0.24
Dielectric constant	3.07	3.17
Dissipation factor	0.0008	0.0012
Insulation resistance, ohm-cm^2	3.10^{13}	3.10^{12}
Surface density, g/cm^2	0.30	0.30
Film stress, V/mil		
pk	825	825
rms	583	583

The Component Research Company, manufacturer of the metallized film capacitors for the 400 Hz ac application, wound all the pads and performed capacitance, dissipation factor, leakage current, and ac dielectric withstanding voltage tests on these components. There were 216 Ultem pads and 338 Kimfone* polysulfone pads.

These capacitors had virtually zero space factor and were essentially all film between the electrodes. Because of this, a great deal was learned about the relative merits of a film by studying the behavior of such capacitors, since material interactions were not a problem.

Initial life tests were at high temperatures of about 190°C and 150°C. In both instances, catastrophic failure occurred within a few minutes. Other data indicated also that the upper limit for Ultem is less than 150°C.** The third test was conducted at 125°C with ten parts of each type. The applied voltage was 140 Vrms 400 Hz. A plot of the data is shown in Figure 2. The test ran for 3,408 hours. It can be seen that five polysulfone capacitor pads failed indicating variable quality of the film. None of the Ultem pads failed.

The test was continued by raising the temperature in 5°C steps (and 140 Vrms) until all the parts failed. The test data is given in Appendix C. A plot of the data at the final temperature of 155°C is shown in Figure 3.

Although Ultem performed satisfactorily at 125°C, this temperature is close to its upper limit of safe operation. The results, however, indicate that Ultem would be a suitable substitute for the polysulfone film which is no longer available from Schweitzer.

Because of its high temperature limitations Ultem cannot be used for this program. Furthermore, the construction using many wound pads is inadequate thermally. The reliability of the large number of soldered interconnections also will be unsatisfactory. A new design approach is required to meet the goals of this program.

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*Registered trademark of Schweitzer Div., Kimberly-Clark Corporation.

**Component Research Co., Inc., private communication.

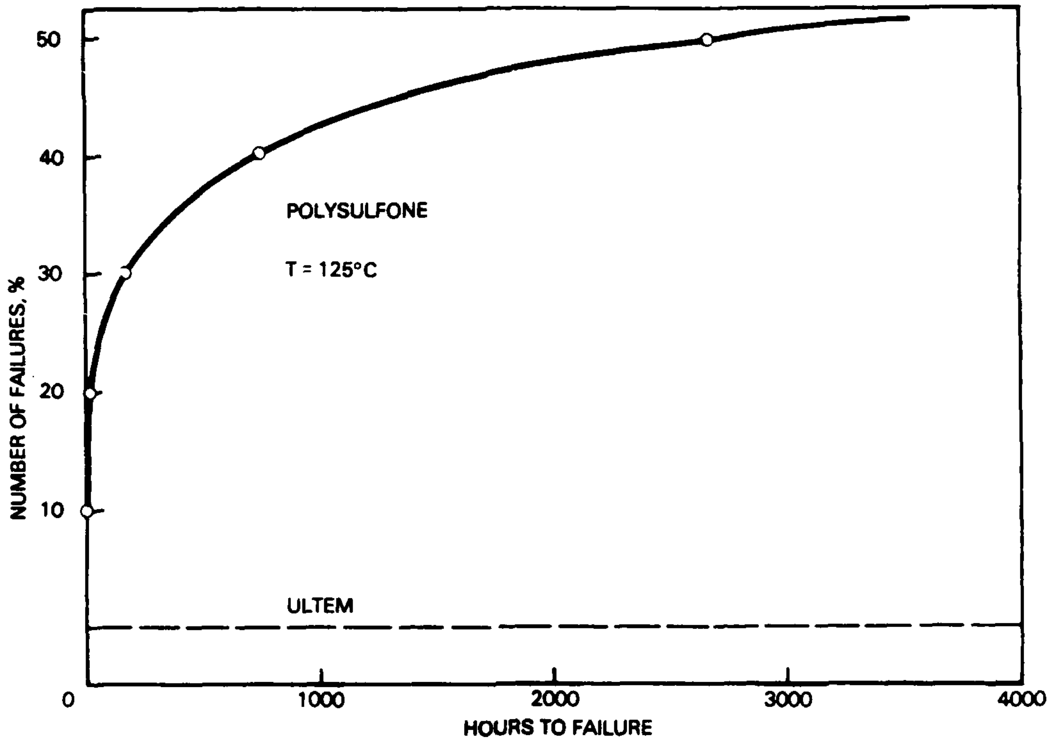


Figure 2. Life time of metallized polysulfone and Ultem film capacitors at 140 Vrms 400 Hz and 125°C. Sample size 10 each.

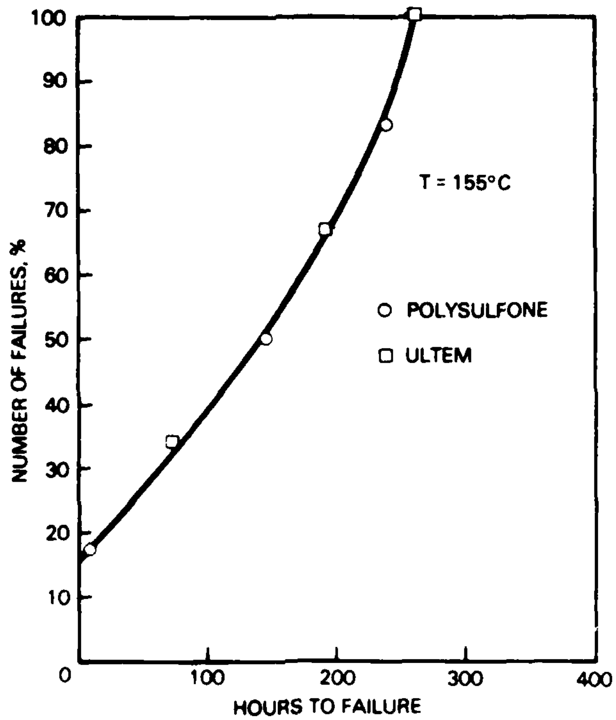


Figure 3. Life time of metallized polysulfone and Ultem film capacitors at 140 Vrms 400 Hz and 155°C. Total sample size 6. (Prior to exposure at 155°C, parts had survived increasing temperature 125°C to 150°C for 4368 hours.)

III. MATERIALS DEVELOPMENT

CANDIDATE MATERIALS

The upper temperature limit for films for this application must exceed 200°C, the hot-spot temperature of the film being somewhat higher depending on the heat conduction. To be a candidate, the film must 1) be capable of operating at this temperature continuously, 2) not experience excessive electrical loss, and 3) be compatible with the other construction materials.

The physical and electrical properties of candidate dielectric films is shown in Tables 3 and 4. Figure 4 gives the dissipation factor versus temperature for these films.

The melting points of all the candidate films are quite high. However, the maximum temperatures for capacitor use are considerably lower. For example, the maximum operating temperature for capacitors made with Ultem or polysulfone is only 125°C as compared to melting points of 220°C and 315°C, respectively.

The three remaining candidate materials appear to meet the general requirements:

1. Kapton-H (polyimide)
2. Mica paper
3. Teflon FEP and PTFE.

Teflon has good properties for this application. The dissipation factor is very low and the upper temperature limit is adequate. Teflon FEP as thin as 0.3 mil is available. Teflon PTFE is thicker. These films would require some evaluation, but probably would be satisfactory if they can be obtained thin enough. Teflon flows under pressure (cold flows) and for this reason is deemed unsuitable for this application. In addition, Teflon has an extremely

TABLE 3. PHYSICAL PROPERTIES OF CANDIDATE CAPACITOR FILMS

Property	Ultem	Polysulfone	Kapton-H	Mica Paper	Teflon FEP
Melting point, °C	220	315	None	Decomposes 975	253-272
Density, g/cm^3	1.27	1.24	1.42	1.6	2.12 to 2.17
Glass transition temperature, °C	215	190	None below 300	-	127
Thermal conductivity, cal/cm^2 sec (°C/cm)	5.26×10^{-4}	6.2×10^{-4}	3.72×10^{-4}	6 to 12×10^{-4}	6.0×10^{-4}
Thermal expansion, in/in °C	56×10^{-6}	52 to 55×10^{-6}	20×10^{-6} MD* 60×10^{-6} TD*	17 to 25×10^{-6}	93×10^{-6}

*Machine and transverse direction

TABLE 4. ELECTRICAL PROPERTIES OF CANDIDATE CAPACITOR FILMS

Material	Dielectric Constant 25°C, 1 kHz	Dissipation Factor 25°C, 1 kHz	Volume Resistivity, ohm-cm	Dielectric Strength, V/mil
Ultem	3.15	0.0013	6.7×10^{15}	4000
Polysulfone	3.07	0.0008	5×10^{18}	7500
Kapton-H	4.0	0.007	10^{12}	3000
Mica paper	4.5-5.5	0.0004	10^{14}	4000
Teflon FEP	2.0	0.0001	$>10^{16}$	4000

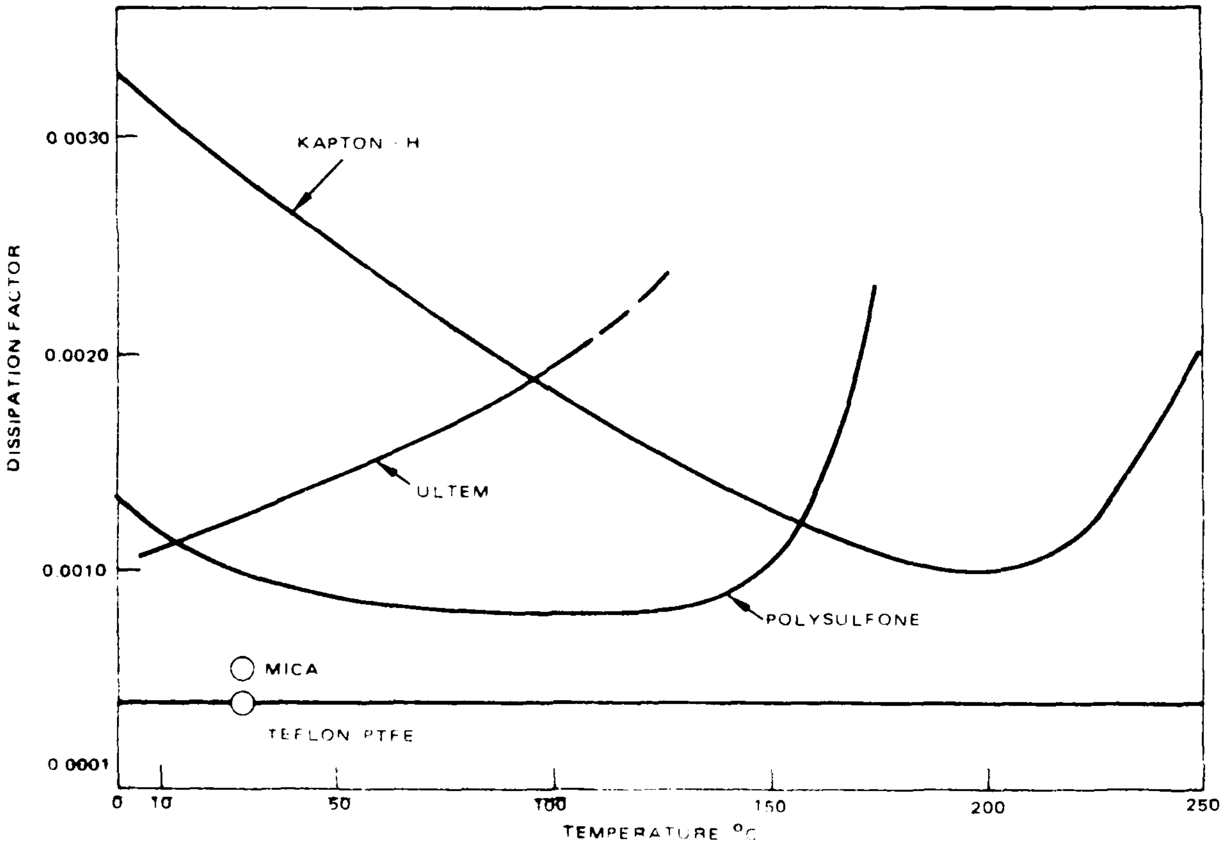


Figure 4 Dissipation factor versus temperature of various dielectric films.

low coefficient of friction, i.e., it is very slippery. It is felt that it would be hard to keep in place, especially during shock or vibration.

MICA PAPER

Mica is a natural mineral which is used in its natural form. Mica paper is an all-mica insulating paper made by flaking the mica with heat and sheeting from a water slurry in a paper-making machine. No binder is used.

Mica paper has the highest temperature limit followed by Kapton-H and Teflon. It decomposes completely at 975°C. However, mica gives off water of crystallization at about 500°C and hence probably cannot be used for capacitors at more than 400°C.

For this application it is planned to use the mica paper unimpregnated since the electrical stress will be very low. If it were impregnated, the upper temperature limit would be determined by the impregnant. For example, with Epon 825 epoxy the upper temperature limit is about 150°C in air. The impregnating material would also affect the thermal conductivity.

To evaluate the mica paper a number of capacitors were wound and tested. The results are compared with identical Kapton capacitors in the following section.

KAPTON

Kapton and mica paper both meet the 200°C operating temperature and the higher hot spot temperatures. The electrical and thermal characteristics are given in Table 5.

The operating temperature of Kapton is limited by its dissipation factor. The variation of dissipation factor with temperature is shown in Figure 5. The dissipation factor reaches a minimum value at about 200°C. Above 250°C it increases rapidly to unacceptable values. In addition, Kapton degrades slowly in air above 225°C. It can be used for this application, if the heat conduction is sufficient to limit the hot spot temperature to about 230°C.

TABLE 5. ELECTRICAL AND THERMAL CHARACTERISTICS OF MICA PAPER AND KAPTON-H

Parameter	Mica	Kapton-H
Melting point, °C	Decomposes 975	None
Density, g/cm^3	1.6	1.42
Thermal conductivity, cal/cm^2sec (°C/cm)	6 to 12 x 10^{-4}	3.72 x 10^{-4}
Thermal expansion, in/in °C	17 to 25 x 10^{-6}	20 x 10^{-6} MD* 60 x 10^{-6} TD*
Dielectric constant	4.5 to 5.5	4.0
Dissipation factor, 25°C, 1 kHz	0.0004	0.007
Dielectric strength, V/mil	4000	3000
Volume resistivity, ohm-cm	10^{14}	10^{12}

*Machine and transverse direction

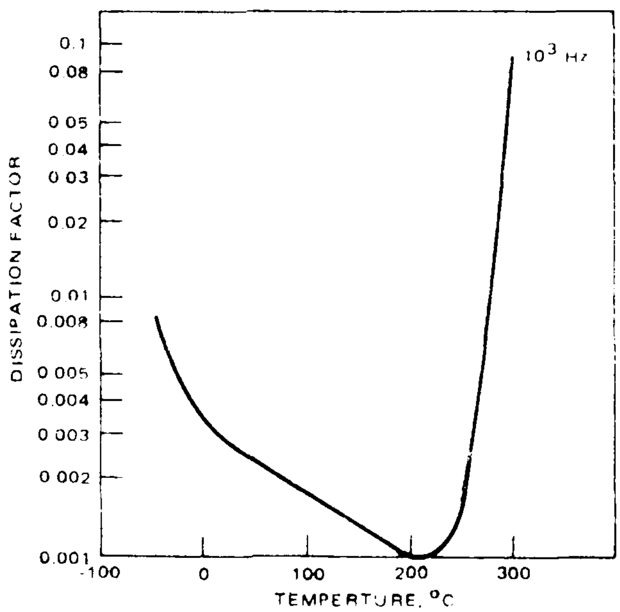


Figure 5 Dissipation factor of Kapton H film versus temperature

To evaluate the Kapton film, some Kapton capacitors (pads) were made and tested along with an equal number of identical mica paper capacitors.* Six pads each were wound with 150 turns of 30 gauge (0.0003 inch) Kapton and 0.5 mil (0.0005 inch) mica paper. Both films were 3-3/4 inches wide. The foils were extended with about 1/8-inch margins. The pads were pressed flat after winding.

Electrical measurements were made of capacitance (C), dissipation factor (DF), insulation resistance (IR), and dielectric strength. The data for the Kapton capacitors is shown in Table 6. This data is in agreement with the DuPont specifications for Kapton-H film. The DuPont specifications of electrical property tolerances and test methods for Kapton-H film are given in Tables 7, 8, and 9. The complete specifications for Kapton polyimide film for capacitors are shown in Appendix D.

Electrical measurements for the mica paper capacitors is shown in Table 10. It can be seen that the DF is exceedingly high. This is attributed to using nickel tabs for contacting the aluminum foil electrodes.

TABLE 6. ELECTRICAL MEASUREMENTS OF WOUND KAPTON-H FILM CAPACITORS. FILM THICKNESS 0.0003 INCH

Test	Serial Number					
	1	2	3	4	5	6
C @ 1 kHz, μF	2.71	2.83	2.76	2.27	2.83	2.68
D.F. @ 1 kHz, %	0.011	0.008	0.009	0.008	0.007	0.008
I.R. @ 400 VDC for 5 minutes, G	30	30	30	30	28	30
Dielectric strength @ 400 VDC for 1 minute	pass	pass	pass	pass	pass	pass

*Mica paper was manufactured by Corona Films, Inc., 241 Dudley Road, W. Townsend, MA 01474

TABLE 7. DISSIPATION FACTOR OF KAPTON H FILM

DISSIPATION FACTOR (25°C) (Maximum at 1 KHz)

GAUGE AND TYPE		Test Method
30H	.007	Test according to ASTM D-150 using conducting silver paint electrodes two terminal system of measurement. Condition sample to 50% R.H. for 24 hrs. and test at 25°C. Results are based on an average of 5 tests using actual thickness of sample.
50H	.005	
100H	.004	

TABLE 8. INSULATION RESISTANCE OF KAPTON-H FILM

INSULATION RESISTANCE (200°C) (Megohm-microfarads)

GAUGE AND TYPE	MINIMUM (4) AVERAGE	Test Method
30H	45	Measured on 0.5 mfd. unimpregnated, single-layer capacitors. 3 min. total electrification (2 min. charge, 1 min. operation at 100 volts D.C., using General Radio megohm bridge model 544-BS4 or equivalent). Preheat capacitors in oven at 200°C ±1°C for one-half hr. prior to test. Maintain temperature at 200°C ±1°C during measurement of capacitor resistance and capacitance.
50H	30	
100H	15	

TABLE 9. DIELECTRIC STRENGTH OF KAPTON-H FILM

DIELECTRIC STRENGTH (DC) (1)

CRITICAL TEST VOLTAGE	Number of Capacitors Which Must Survive Critical Test Voltage per 20 Capacitors (3)			Test Method
	30H	50H	100H	0.5 mfd. unimpregnated single-layer capacitors are subjected to D.C. voltage at 100 volts/second rate of rise at room temperature and 50% R.H. Tests to be conducted on as-wound units using 2" wide film and a ⅛" arbor. Units failing a 6-volt shorting test shall be discarded.
300	19			
500	16	19		
700		16		
1500			19	
Minimum Average Voltage of 20 Capacitors	900	1200	1800	

REFERENCES

(1) Samples conditioned at room temperature and 50% R.H. for 24 hrs.

(2) Applicable to samples from the same mill roll lot.

(3) This number has been statistically determined. Normally, it will be met by any group of 20 capacitors. However, to definitely prove, statistically, that the specified number has been met for any mill roll lot of materials, it will be necessary to wind 60 capacitors from 3 slit rolls (20 from rolls A and B, 20 from B and C, and 20 from A and C). If the average of the 3 groups is lower than the allowable number, the material is rejectable.

(4) Minimum average of 5 units.

TABLE 10. ELECTRICAL MEASUREMENTS OF WOUND MICA PAPER CAPACITORS. FILM THICKNESS 0.0005 INCH

Test	1	2	3	4	5	6
C @ 1 kHz, μF	2.94	2.98	2.99	3.01	2.98	3.05
DF @ 1 kHz	0.23	0.24	0.25	0.25	0.23	0.24

In addition, the dielectric strength measurements exhibited excessive leakage current. This was due to moisture, since the parts had not been dried. The parts were then dried at 160°C overnight and remeasured. As expected the leakage current after drying decreased to a satisfactory level. The dissipation factor also decreased. Surprisingly, the capacitance was very small. This was felt to be due to the large amount of air present. This was confirmed by calculating the dielectric constant which gave a value of one, about the same as air. This results from 1) the density of unimpregnated mica paper being only about 55 percent of solid mica, and 2) a large amount of air between the many layers.

It appears that mica paper cannot be used dry, i.e., unimpregnated. It would be possible to vacuum impregnate the mica paper with 50 centistoke Dow-Corning 200 silicone oil which has a high temperature limit of 200°C. However, this would complicate the capacitor design and assembly. Therefore, at this time mica paper will not be considered further as a candidate material.

It is evident that of the candidate materials only Kapton meets the general requirements. Therefore, Kapton will be used for the capacitor designs.

POLYMER CLAD FOILS

A new material which was offered during the beginning of the program was a product called Polymer Clad System (PCS) from Enka Industrial, Inc. This product is a two-layer (adhesiveless) substrate consisting of a high temperature, inert polymer film directly bonded to one side of a metal foil. The polymer is a fully aromatic polyimide which is purported to be polymerically equivalent to Kapton. Several metals have been utilized in this system to date, including aluminum, copper, stainless steel, and nickel.

The aluminum/polymer composite has a high bond strength, both at room temperature and at elevated temperatures.

The PCS polymer displays a higher dielectric constant and dissipation factor than comparable gauges of Kapton film. Comparison of the electrical and thermal properties of the PCS polymer on aluminum and Kapton is given in Table 11.

TABLE 11. PROPERTIES OF KAPTON AND PCS POLYMER COATED COPPER

Property	PCS	Kapton	Kapton/Foil*
Dielectric constant	4.0	4.0	4.0
Dissipation factor, 25°C, 1 kHz	0.005	0.007	0.030
Dielectric strength, V/mil	3500	3000	2000
Operating temperature, maximum	220	250	---
Glass transition temperature, °C	---	>300	---
Volume resistivity, ohms	10^{14}	10^{12}	10^{13}
Thermal conductivity, cal/cm^2 sec (°C/cm)	---	3.72×10^{-4}	---
Thermal expansion, in/in °C	17×10^{-6}	20×10^{-6} MD** 60×10^{-6} TD**	---

*Adhesively bonded.
**Machine and transverse direction.

The primary advantage of using such a two-layer system would be a reduction in the number of pieces which must be cut and stacked.

Samples of film supplied by Enka demonstrated that the polyimide could be successfully deposited on 0.0002 inch aluminum foil. Unfortunately, their equipment was designed for heavier material and was unable to wind the 0.0002 inch aluminum without excessive wrinkling. As a result, this interesting material could not be evaluated. (Enka was able to modify their winding equipment to handle thinner foils but too late to be included in this program.)

FOILS

The foils in an ac filter capacitor play a major role in the final temperature of the device. The foils also contribute to the overall weight of the capacitor. There are five basic requirements for the foil:

1. High heat conductance
2. Low resistivity
3. Low density
4. Low chemical reactivity
5. Capability of being electrically joined

The first two requirements, high heat conductance and low resistivity, are needed to attain a minimum hot spot temperature. The third affects the weight. The last two are necessary for performance and reliability.

The requirements for high heat conductance, low resistivity, and low density are evident if these terms are combined to define the conductance per unit mass, σ, using the following formula

$$\sigma = \frac{k}{\rho_e \rho_m} \qquad (3\text{-}2)$$

where ρ_m is the density, ρ_e the resistivity, and k the foil heat conductance. For the capacitor foil, the highest possible value of σ is desired.

The two foils considered for use were aluminum and copper. Their properties are summarized in Table 12.

After reviewing their properties, aluminum is the preferred foil material. Aluminum has the lowest mass resistance; it is chemically nonreactive with the other candidate materials; and it can be either welded or mechanically jointed to provide joints of low electrical resistance.

TABLE 12. PROPERTIES OF CANDIDATE CAPACITOR FOILS

Foil Metal	Volume Resistivity, ρ_e (ohm-cm x 10^{-6})	Density at 20°C, ρ_m (g/cm^3)
Al	2.8 at 20°C 3.9 at 100°C	2.7
Cu	1.8 at 20°C 3.0 at 200°C	8.9

The principal manufacturer of technical grade aluminum foil is National Aluminum (Republic Foil).* The standard alloy used in the manufacture of aluminum foil for paper and film wound capacitors is Alloy 1145. For these wound capacitor applications the foil is fully annealled after final slitting.

The maximum chemical composition limits of Alloy 1145 are given below:

Silicon + Iron	Copper	Manganese	Other	Minimum Aluminum
0.55%	0.05%	0.05%	0.03%	99.45%

The representative physical properties of Alloy 1145 are shown below:

Thermal Conductivity (cal/sec/cm^2/cm/°C)	Electrical Conductivity (% copper)	Tensile Strength (psi)
0.55	59	10,000

The direct current electrical resistance for various thicknesses of Alloy 1145 is shown in Table 13.

During fabrication of the capacitors it was found that it was difficult to cut the annealled foil cleanly. It was recommended that T19 temper which is full hard be used instead of the annealled foil for this application. The problem of cutting the foil cleanly is discussed in Section VI.

*National Aluminum, 55 Triangle St., Danbury, CT 06810.

TABLE 13. ELECTRICAL RESISTANCE OF ALLOY 1145 ALUMINUM FOIL VERSUS THICKNESS

Nominal Thickness, in.	Resistance per Foot for 1 Inch Width, ohms/ft
0.00017	0.124
0.00020	0.105
0.00023	0.091
0.00025	0.084
0.00030	0.070
0.00050	0.042

IV. CAPACITOR DESIGN

CAPACITOR DESIGN REQUIREMENTS

To meet the goals of this program, a new capacitor design is required. This design first must manage the thermal problem. The internal dielectric heat must be conducted efficiently to the outside. The hot-spot temperature must be less than the upper limit of the dielectric material when the ambient temperature is 200°C. Only mica paper, Teflon, and Kapton appeared to be possible candidate materials for operation at these conditions. Teflon is unsuitable because it cold flows and is extremely slippery. Mica paper is also unsuitable unless it is impregnated. This will limit the operating temperature and complicate the capacitor designs.

Kapton-H film is felt to be adequate to meet the goals of this program. Its operating temperature will be limited by its dissipation factor to about 230°C. This will recessitate efficient thermal conduction to keep the hot-spot temperature within acceptable limits.

The major electrical and thermal design requirements are shown in Table 14.

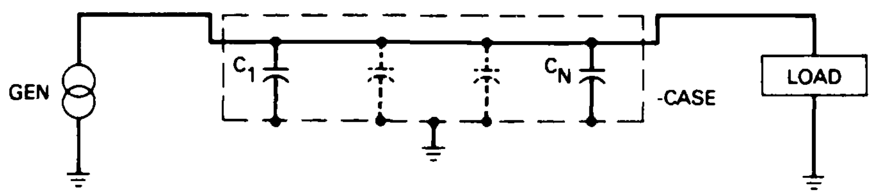
DESIGN CONCEPT

The conventional approach for a line filter is shown in Figure 6a. A heavy bus is provided to carry the line current. About 50 or 60 conventional wound capacitors would be connected from the bus to ground to make up the 180 μF of capacity.

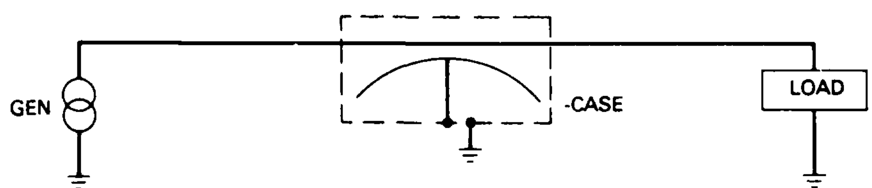
The proposed design is shown in Figure 6b. Figure 7 shows the arrangement of the capacitor foils. A single capacitor pad with one of the plates as the high current conductor can be seen. The other plate is connected directly to ground and the cold plate. This arrangement has the

TABLE 14. ELECTRICAL AND THERMAL REQUIREMENTS

Paramater	Requirement
Capacitance	180 μF and 45 μF
Insulation resistance	695K megohm
DC resistance	0.3 milliohm max
Maximum voltage	150 Vrms
Frequency	400 Hz
Dissipation	0.15% max at 25°C
Feedthrough current	224 amp cont, 435 amp for 5 seconds
Operating temperature	-55 to +200°C min
Operating voltage	120 Vrms



a. Conventional



b. Proposed

Figure 6. Schematic diagrams of filter capacitor designs.

advantage of reducing the number of interfaces in the heat conducting path as compared to the multiple pads normally used.

The proposed pad construction is shown in Figure 8. The design calculations are given in Appendix E. The pad is made up of alternate sheets of Kapton and aluminum foil. One-half of the aluminum foils are clamped

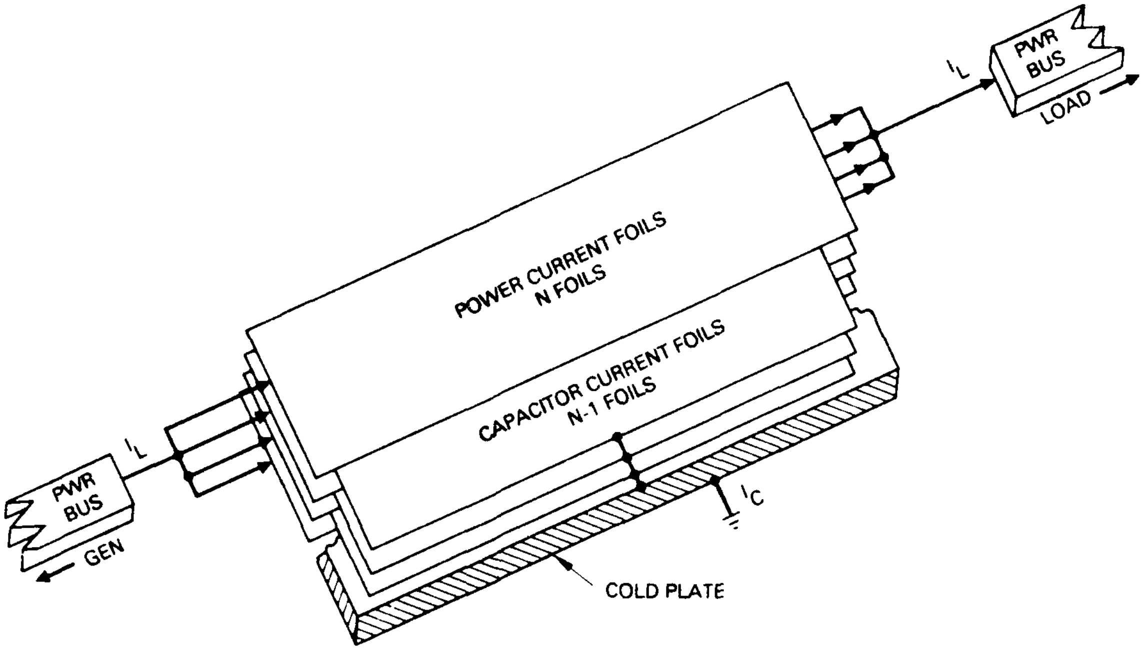


Figure 7. Schematic diagram showing arrangement of proposed capacitor foils.

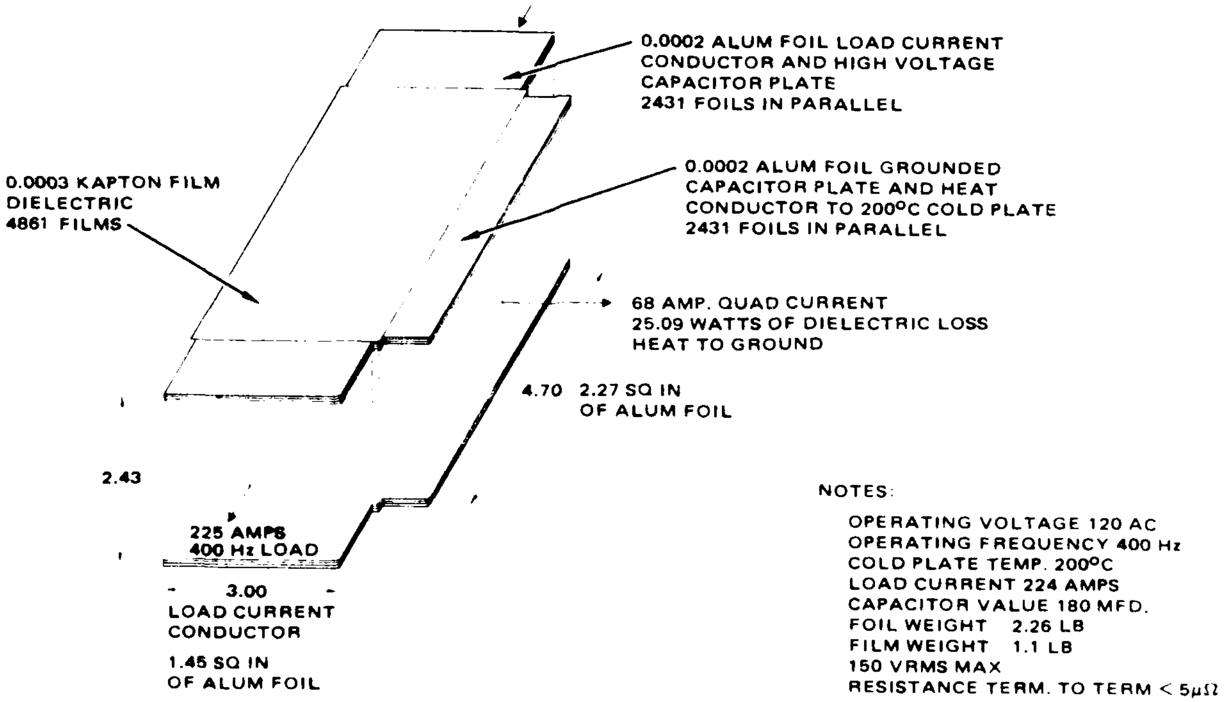


Figure 8. Diagram showing capacitor (pad) construction.

together at each end to form the current conductor through the capacitor. The other half are clamped together and connected to the bottom of the case, which is in close contact with the 200°C cold plate. The physical details of the proposed connection scheme are shown in Figure 9.

Although the physical stacking and handling of the large number of pieces of film and foil may be difficult compared to the conventional wound pads, some mechanical aids can assist in the stacking process. One advantage of the design is that the foil and film can be inspected for defects before using it.

The rationale for the selection of materials is as follows: Although the Kapton could be thinner than proposed from a voltage breakdown consideration, it cannot be purchased thinner than 0.0003 inch. The other ingredient in the pad is aluminum foil. Here again, the standard foil thickness of 0.0003 inch is more than sufficient for the current conductor resistance and the thermal path to conduct heat. Foil 0.00017 and 0.0002 inch can be obtained if a minimum quantity is purchased. The proposed design is based on foil 0.0002 inch thick.

The volume of the proposed design will be smaller than the 120 μF capacitor, made by Components Research Company, scaled up to 180 μF. This

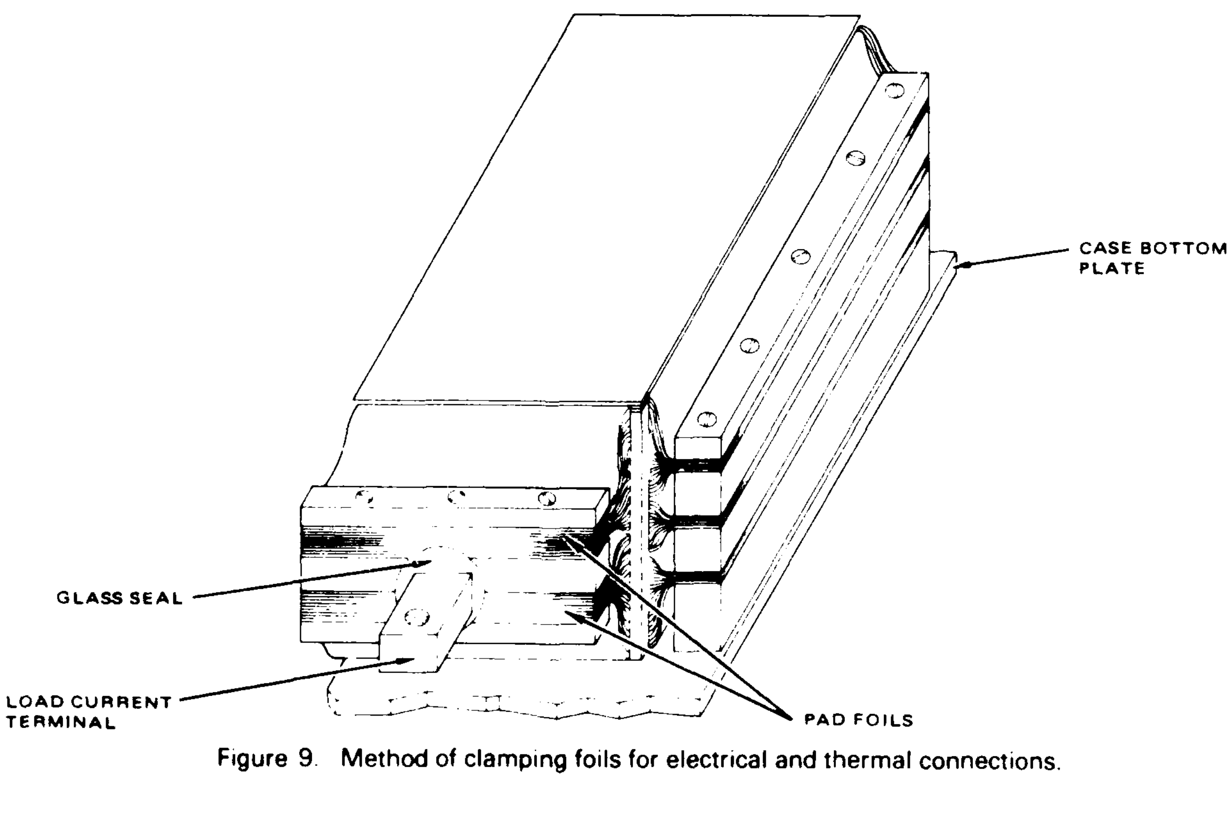


Figure 9. Method of clamping foils for electrical and thermal connections.

can be shown as follows. The volume of the 120 μF filter capacitor made by Components Research Company is

$$V = 5.5 \text{ in. long} \times 2.125 \text{ in. wide} \times 2.625 \text{ in. high}$$

$$= 30.7 \text{ in}^3$$

The volume of an equivalent capacitor of 180 μF is

$$V = \frac{180}{120} \times 30.7 = 46.1 \text{ in}^3$$

From Figure 7 the volume of the proposed design is

$$V = 5.4 \text{ in. long} \times 3.25 \text{ in. wide} \times 2.4 \text{ in. high}$$

$$= 42 \text{ in}^3$$

The dimensions of the capacitor as shown are arbitrary and can be changed depending on the system requirements.

One seeming alternate approach was to use metallized Kapton film. This possibility was considered, but was not pursued for the following reasons. The metallization would have to be extraordinarily heavy to limit the hot-spot temperature. The adherence of the aluminum to the Kapton and the long term stability of the electrical resistivity and the thermal conductivity of the aluminum would have to be determined. In addition, the method for making the connections to the case and current conductor would have to be established. Making reliable connections to the extended foils in a conventionally wound capacitor is even more difficult. Both epoxy and flame-sprayed large connections would have to be evaluated at high temperatures for long periods.

THERMAL MANAGEMENT

The current capacitor fabrication technique consists of tightly winding alternating layers of dielectric, kraft paper and metal foil which results in a poor thermal design. There is little room for optimization studies although such were undertaken analytically by Hughes and reported upon in detail*. Large detailed thermal analyses such as those are readily performed with generalized thermal analyzer programs such as CINDA and TAP 3. These are finite differencing programs that provide temperature distribution predictions in the physical system being modelled. In addition, we have developed subprograms that automate the generation of the thermal models, the processing of the input and output thermal data enabling a dramatic reduction in the cost and turnaround time for the optimization of thermal designs and tradeoff studies.

These sophisticated analytical tools were available, if they were required. However, the proposed capacitor design will result in small internal temperature rises which are readily calculated by hand.

Based on the proposed design shown in Figure 10, there will be 4,861 sheets of Kapton dielectric and a total of 4,862 layers of aluminum foil. The dielectric and foil layers will be 0.0003 and 0.0002 inch thick, respectively. Alternate layers of the foil go to the positive terminal and the ground terminal, respectively. Assuming that the positive terminal does not constitute a significant heat sink path, the heat dissipated in the dielectric is conducted primarily to the ground terminal via 2,431 sheets of aluminum foil.

If the total dielectric loss in the capacitor is Q watts it will be distributed uniformly within 4,861 layers of dielectric. As shown in Figure 11, for each layer of dielectric one layer of aluminum foil will conduct the heat out to the ground terminal. Thus, there are two additive temperature gradients which constitute the overall gradient from X to Y (see Figure 10) to consider, one in the dielectric and one in the aluminum foil.

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*"Capacitors for Aircraft High Power," United States Air Force Report AFWAL-TR-80-2037, Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio, p. 121-135, January 1980.

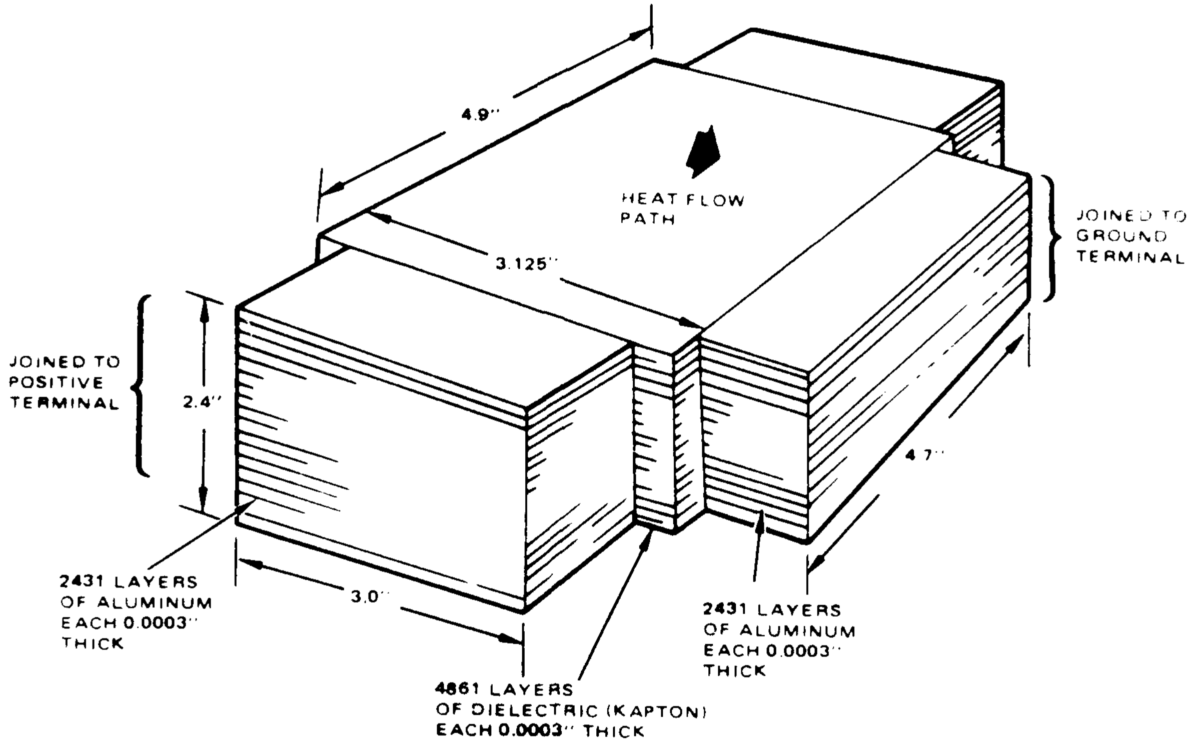

Figure 10. General arrangement showing primary heat flow path.

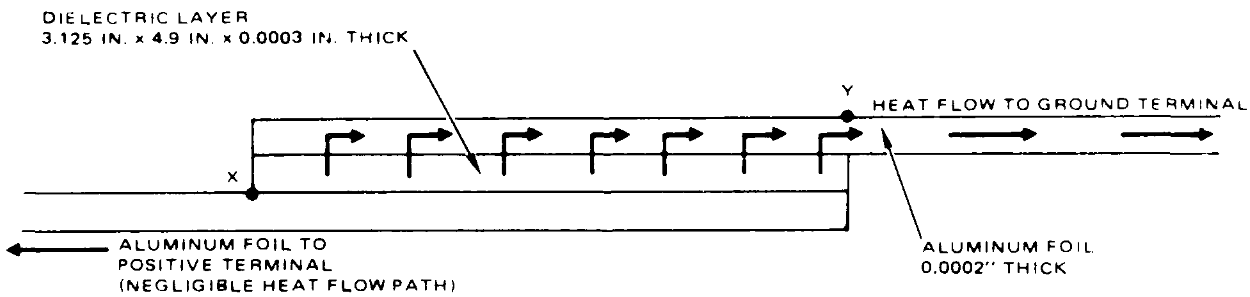

Figure 11. Heat flow path for each dielectric layer (thickness exaggerated).

Each temperature gradient is given simply by the formula

$$\Delta T = \frac{1}{2} \frac{QL}{KA} \tag{3-3}$$

where:

Q = conducted heat

L = conductive path length

A = conducted cross sectional area

K = material thermal conductivity

The factor 1/2 accounts for the fact that the heat is uniformly distributed within the dielectric layer and also enters the aluminum uniformly before exiting the capacitor body. In reality a third gradient, at the dielectric/foil interface, would be present. However, since in the assembly of each capacitor care must and will be taken to remove all the interstitial air, and the materials are reasonably compliant, this interface resistance will be negligible.

For the two gradients the following parameters apply:

Kapton	Aluminum Foil
$K = 4.136 \times 10^{-3}$ W/in°C	$K = 4.27$ W/in°C
$L = 0.0003$ in.	$L = 3.125$ in.
$A = 3.125 \times 4.9$ in^2	$A = 4.9 \times 0.0002$ in^2

For a total dissipation of 25.09 watts (see Appendix E) or 5.16×10^{-3} watts in each of the 4,861 dielectric layers, the temperature gradients are as follows:

$$\Delta T \text{ in the dielectric} = 1.22 \times 10^{-5}\ ^{o}C$$

$$\Delta T \text{ in the aluminum foil} = 1.93^{o}C$$

This shows that the entire temperature gradient will be occurring within the aluminum foils and, allowing for added length and compression at the grounding terminal, will amount to only a few degrees centigrade.

The marked improvement in thermal design is due to the fact that the uniformly distributed dielectric losses have to be conducted through only a single layer of dielectric.

CAPACITOR DESIGNS

This section presents the design details for the two different ac filter capacitors, a 45 μF capacitor and a 180 μF capacitor. These components were designed for state-of-the-art airborne applications which will have a higher operating temperature than presently available.

The 45 μF capacitor was designed first using the results of the early assembly work. The design is very conservative. Ample space was left for making the terminations, and the cover was made high enough to allow for 0.0005 inch Kapton, a thick pressure plate, and bolts for clamping. The design will be refined after some units have been assembled and tested.

The larger capacitor was scaled directly from the 45 μF capacitor. The dielectric dimensions were selected arbitrarily 1) for ease of assembly and 2) for the best overall shape.

45 μF CAPACITOR DESIGN

The design comprises an aluminum baseplate which also serves as a heat sink path, the capacitor pad made up of the aluminum foil and Kapton, an aluminum pressure plate to compress the pad, and an aluminum case to enclose the capacitor (pad).

The design is based on using 30 gauge (0.0003 in.) Kapton 3-3/4 inches wide with aluminum foil 0.00017 inch by 3-1/2 inches wide. The margins are 1/8 inch.

The number of layers can be estimated from Equation 1. A sample calculation is presented in Appendix E. This approach underestimates the number of layers. This can be understood by recognizing that there is some air between the layers. Since the dielectric constant of air is less than that of Kapton, the dielectric constant of the combination will be less than that of Kapton alone. One way of compensating for the lower dielectric constant is to increase the number of layers.

The number of layers for this design was estimated by extrapolating the capacitance of S/N 3, which was a 500 layer pad made from 30 gauge (0.0003 in.) Kapton 3-3/4 inches wide. The margins were 1/8 inch, making the active dielectric 3-1/2 x 3-1/2 inches. The measured capacitance was

10.44 μF at 1,000 Hz. The calculated number of layers for 45 μF then was 2,155 layers. The height of the pad was estimated from the number of layers. The length and width of the capacitor were obtained from the size of the Kapton (3-3/4 in.) plus allowances for the terminations and feedthrough connectors.

A drawing of the 45 μF capacitor assembly is shown in Figure 12. The pressure plate is positioned with four studs (fastened to the baseplate) which are used to compress the pad. The electrical connections are made by clamping the aluminum foil. As shown, the ground foil is fastened to the baseplate. The other set of foils is clamped and connected to the feedthrough connectors. The cover is welded all around, to the baseplate and two end plates to hermetically seal the capacitor. Four mounting pads are provided for attaching the capacitor to the cold plate. The overall case dimensions are 5.9 x 5.4 x 3.4 inches. Detail drawings of the 45 μF capacitor are shown in Appendix G.

180 μF CAPACITOR DESIGN

The 180 μF capacitor design is similar to the 45 μF capacitor design but it is larger.

The design is based on using 30 gauge (0.0003 in.) Kapton 4-1/2 inches wide with aluminum foil 0.00017 inch by 4-1/4 inches wide. The margins are 1/8 inch.

The number of layers for this design was 5,870, extrapolated from the 45 μF capacitor design. From the number of layers the height of the pad was estimated.

The length and width of the capacitor were obtained from the size of the Kapton (4-1/2 in.) plus allowances for the terminations and feedthroughs.

A drawing of the 180 μF capacitor assembly is shown in Figure 13. The overall case dimensions are 6.62 x 6.12 x 5.50 inches. Detail drawings of the 180 μF capacitor are given in Appendix H.

CASE DESIGN

The case to enclose the capacitor (pad) consists of a base, cover, and two terminal end plates. The parts will be made from 6061-T4 aluminum alloy

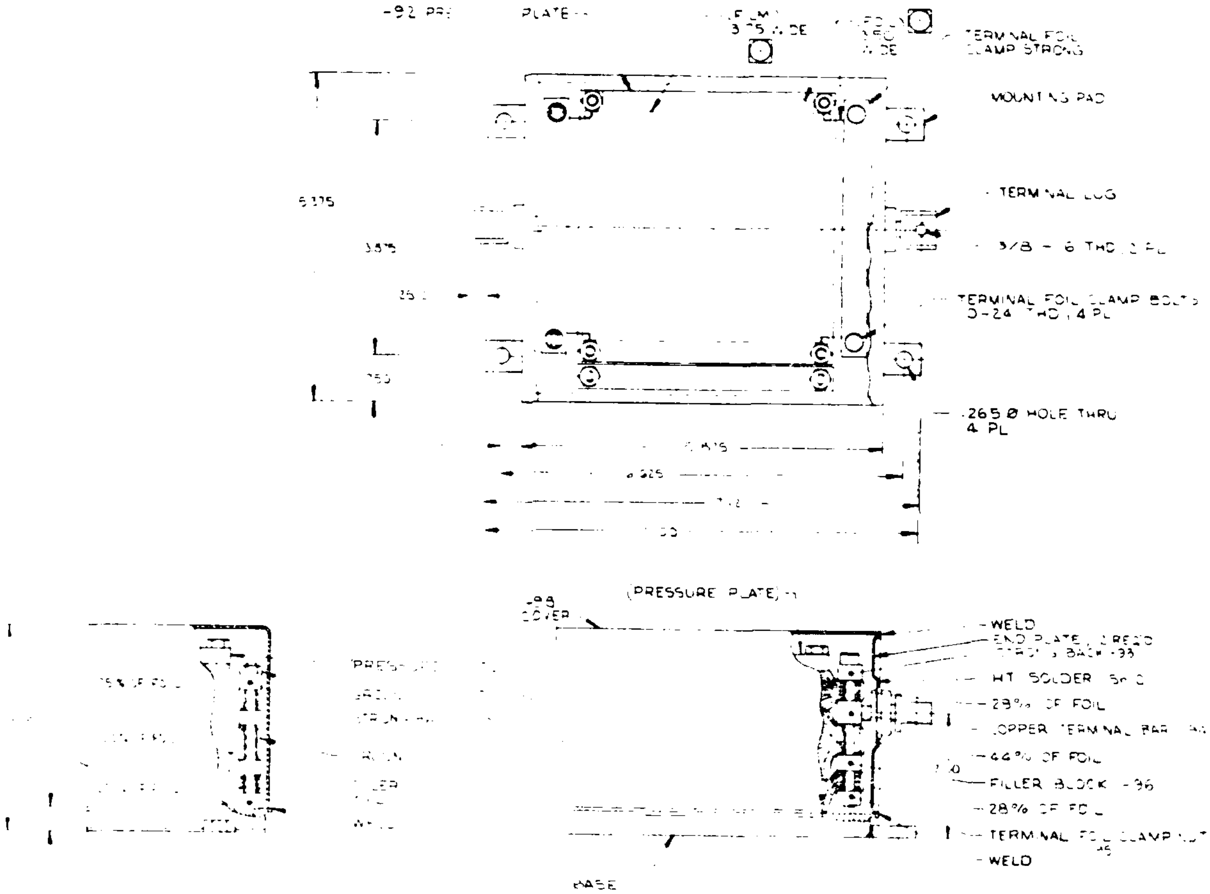

Figure 12. 45 μF capacitor assembly.

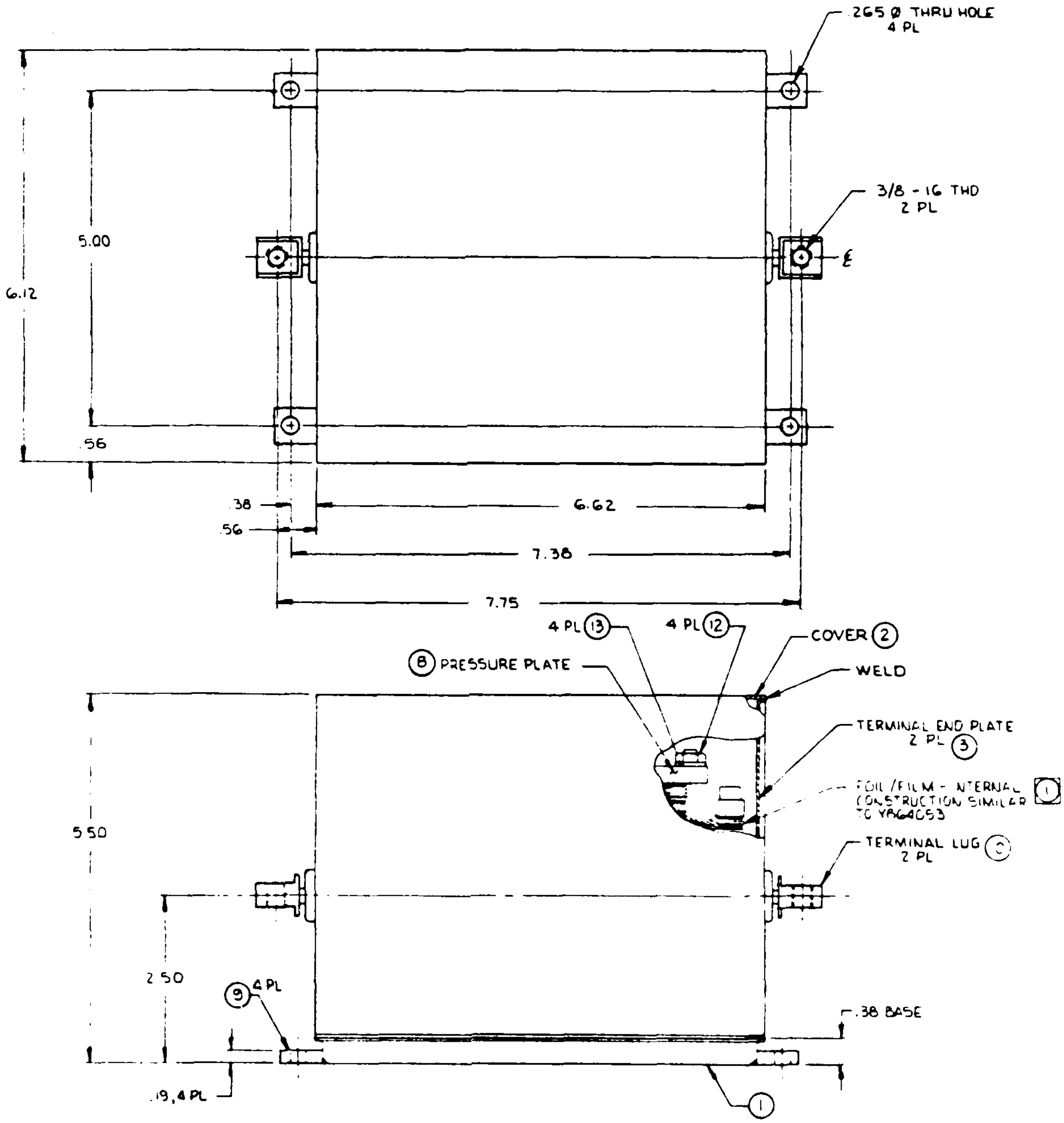

Figure 13. 180 μF capacitor assembly.

and welded together as shown in Figure 11. The capacitor is attached to the base, which serves as a heat sink path. The line foils are connected to the terminal end plate feedthroughs. The grounded foils are attached to the base.

To prove the design a prototype case was fabricated. Figure 14 shows the end plate with the feedthrough connector attached with high temperature solder. The aluminum end plate was electrodeless nickel plated and trimmed before soldering.

The cover is designed to be welded to the base plate. At the time the case is assembled the capacitor will already be attached to the base plate. To ensure that the capacitor will not be overheated during welding, the maximum base plate temperature was measured with Tempilaq*, a temperature indicating liquid. The cover and base plate with Tempilaq indicators is shown

Figure 14. Photograph of end plate and feedthrough assembly.

*Manufactured by Tempil Corporation, 132 West 22nd Street, New York, NY

in Figure 15, after welding. The temperature indicators were 300°F, 400°F, and 500°F. A plot of the temperature profile is given in Figure 16. It can be seen that the heat from welding is dissipated effectively. The temperature of the base plate by the capacitor during welding will be less than 300°F (149°C). This is below the 200°C operating temperature of the capacitor.

A view of the case with the end plate feedthrough assembly in position for welding is shown in Figure 17.

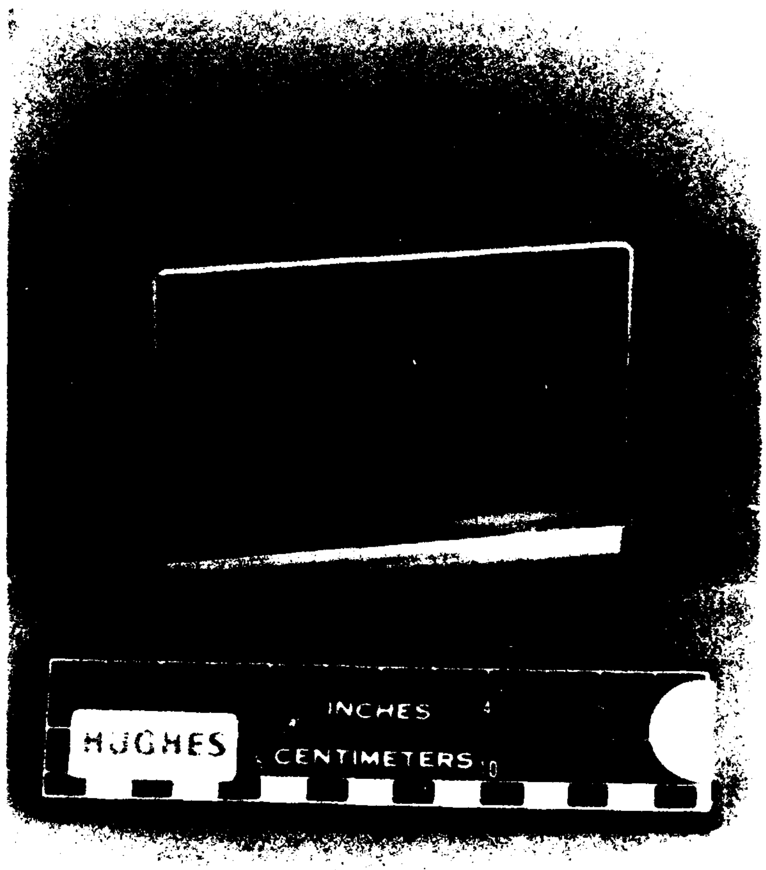

Figure 15. Cover and base plate assembly with Tempilag temperature indicators, after welding.

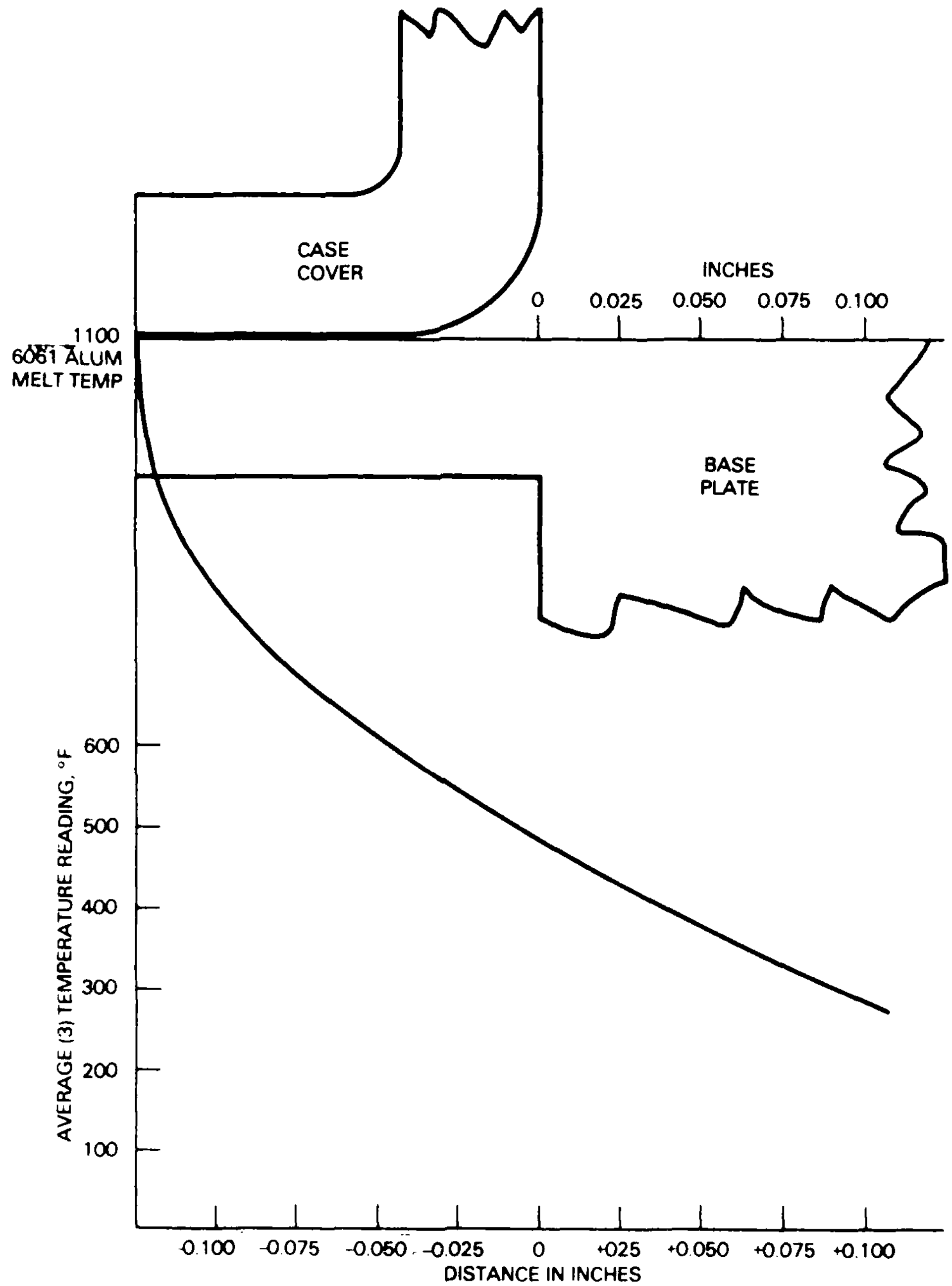

Figure 16. Temperature profile on capacitor case base plate during weld sealing operation.

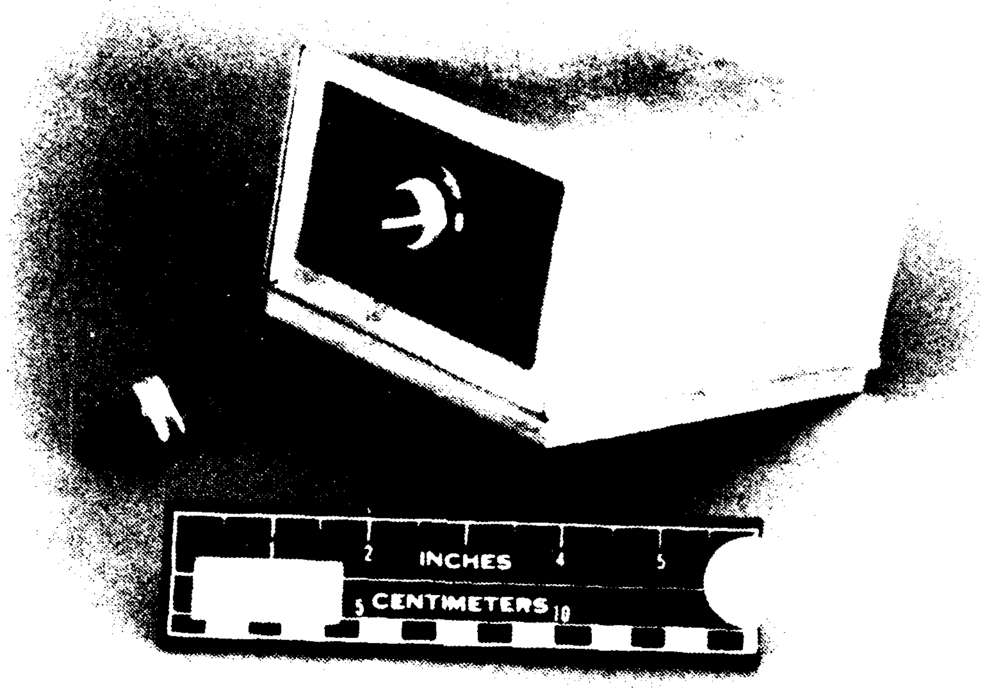

Figure 17 Capacitor case

Pressure calculations indicate only a modest increase in the internal pressure of the case at the upper temperature limit of about 230°C. If the case is filled to one atmosphere of pressure at room temperature (294°K), then the increase in pressure at 230°C (503°K) is

$$\frac{P_1}{P_2} = \frac{294}{503}$$

if

P_1 = 1 atmosphere

then

P2 = 1.7 atmospheres = 25 psi

The net pressure is then

25 - 14.7 = 10.3 psi

V. CAPACITOR TEST PLAN

INTRODUCTION

As described in the statement of work, the capacitor test plan (presented in its entirety in Appendix F) is intended to provide the test procedures describing the performance tests to be performed for both types of capacitors. These tests will establish the capacitors' electrical characteristics. In addition, performance capabilities will be determined under limited environmental conditions. Burn-in tests and life tests at 200°C will demonstrate that the design is good for high temperature operation. (Moisture resistance, salt spray, fungus, vibration, and mechanical shock will not be performed.)

Two different types of assemblies will be tested to provide better quality control and reliability. Capacitor pads will be inspected during manufacture followed by acceptance tests of the complete encased capacitor assembly.

The following tests will be carried out as performance tests:

- Visual and mechanical examination
- Capacitance
- Dissipation factor
- Dielectric withstanding voltage
- Insulation resistance
- Thermal shock
- Seal
- Terminal strength
- Burn-in
- Life

These are explained briefly in the remainder of this section.

PERFORMANCE TESTS

Careful visual and mechanical examination will ensure that all parts and assemblies are of good workmanship, free of visible defects, and in accordance with the drawings/specifications.

Capacitance and DF measurements will be conducted per MIL-STD-202F method 305 at 1,000 Hz using an HP 4262A digital LCR meter. Measurements will be made during capacitor fabrication and during testing of capacitor assemblies.

The dielectric withstanding voltage test will be conducted per MIL-STD-202F, method 301, at 168 Vrms. This test consists of the application of a voltage higher than rated voltage for a specific time between mutually insulated portions of a component part or between insulated portions and ground. This test is used to prove that the component part can operate safely at its rated voltage and withstand momentary overpotentials. When a component is faulty, application of the test voltage will result in either breakdown or deterioration.

Insulation resistance tests will be conducted per MIL-STD-202F, method 302, at 20 Vdc.

The insertion loss test will measure the loss obtained when the capacitor is connected into a transmission system. The loss is represented as the ratio of input voltage required to obtain constant output, in the specified 50 ohm system. Tests will be conducted per MIL-STD-202A at 400 Hz.

Terminal strength tests will be performed to determine whether the design of the terminals and their method of attachment can withstand one or more of the mechanical stresses to which they will be subjected during installation. The torque exerted will disclose poor workmanship, faulty designs, and inadequate methods of attaching terminals to the body of the part. Tests will be conducted per MIL-STD-202F, Method 211A.

Thermal shock tests will be conducted per MIL-STD-202F, Method 107G. The test will consist of five cycles from -65 to +200°C with a 1-hour exposure at the temperature extremes.

The seal test will determine the effectiveness of the welds and other seals of the case which enclose the capacitor. The specified test condition

is a bubble test in heated oil. Tests will be conducted per MIL-STD-202F, Method 112D, at 125°C. The nominal sensitivity will be about 10^{-5} atm cc/sec.

Capacitors will be burned in at 150 Vrms at 200°C for 96 hours prior to life test.

The life tests will be conducted to demonstrate the applicability of the developed capacitors to the particular engineering problems posed by service at 200°C ambient. The test conditions will be rated voltage and 200°C for 1,000 hours.

ORDER OF TESTING

The tests will be conducted in the following time phase:

Capacitor Pad Assemblies

I: Visual and mechanical

C, DF, IR

Dielectric withstanding voltage } Simultaneously

Insertion loss

Capacitor Assemblies

II: Visual and mechanical

C, DF } Simultaneously

Terminal strength

III: Thermal shock

IV: Seal test

V: Burn-in

VI: Life

VII: C, DF

VI. CAPACITOR FABRICATION

INTRODUCTION

Two kinds of capacitors were fabricated, 1) experimental or developmental pads and 2) prototype deliverable capacitors. The former were used to develop the procedures and processes needed. The latter were made to demonstrate that the capacitors will meet the design goals. A summary of the capacitor fabrication is shown in Table 15. The first six pads made were experimental. The remaining pads incorporated the processes and procedures that had been developed.

The first equipment designed was to cut the film and foil to size. The base of the capacitor would serve as a stacking fixture. The first pads made

TABLE 15. SUMMARY OF CAPACITOR FABRICATION

S/N	C, μF	Number of Layers	Area of Dielectric, in^2	Thickness	
				Kapton, mil	Foil, mil
1		500	9.75	0.5	0.25
2	5.6	500	9.75	0.5	0.25
3	10.4	500	12.25	0.3	0.25
4		200	12.25	0.3	0.25
5		200	12.25	0.3	0.17
6		100	12.25	0.3	0.17
7	22.5	1300	12.25	0.3	0.17
8	45.0	3500	12.25	0.5	0.17

developed shorts, which were found to be due to aluminum shards from the shears. Although the cutting process was changed to eliminate the fragments, the shorts persisted and were traced to particles in the rolls. In addition, it appeared that some of the shorts were probably due to pin holes and thin spots in the Kapton. Therefore, it was decided to use the heavier 0.5 mil Kapton (S/N 8) which successfully circumvented the problem.

FILM AND FOIL CUTTING APPARATUS

The capacitor design is simple and the assembly operations required are straightforward. Apparatus to cut the film and foil to the correct size is necessary. The design of this apparatus is presented in the remainder of this section.

The cutting apparatus was designed to dispense a set amount of film or foil which then can be cut off and stacked to form the capacitor. An assembly drawing of the apparatus is shown in Figure 18. Detail drawings are given in Appendix I. The film or foil is held against the rubber roll by the pinch roll and spring (48). The handle rotates the rubber roll which, aided by the pinch roll, pulls the film or foil from the reel. The amount of material dispensed is controlled by adjustable stops that limit the movement of the handle. The film or foil is then cut off with the shears and conveyed to the stacking fixture.

During the first tests of the equipment it was found that the shear bent the foil so that it couldn't advance. An air jet was added to straighten the end of the foil and position it so it could advance.

As expected the Kapton acquires a high electrostatic charge (>5,000 volts) while advancing and then sticks to the rubber roll. If it is unpeeled and cut, it curls up and won't lie flat. Initial tests with a portable deionizer unit indicated the film could be discharged readily. This particular model, however, utilized a fan to blow the deionizing air, which made it difficult to handle the film after it was cut.

For our application, a smaller bar type unit which does not require a fan was ordered. It consists of a power supply connected to a bar containing several sharp points which ionize the air around it. The bars are installed near the charged film to neutralize it. Two bars are required, one to

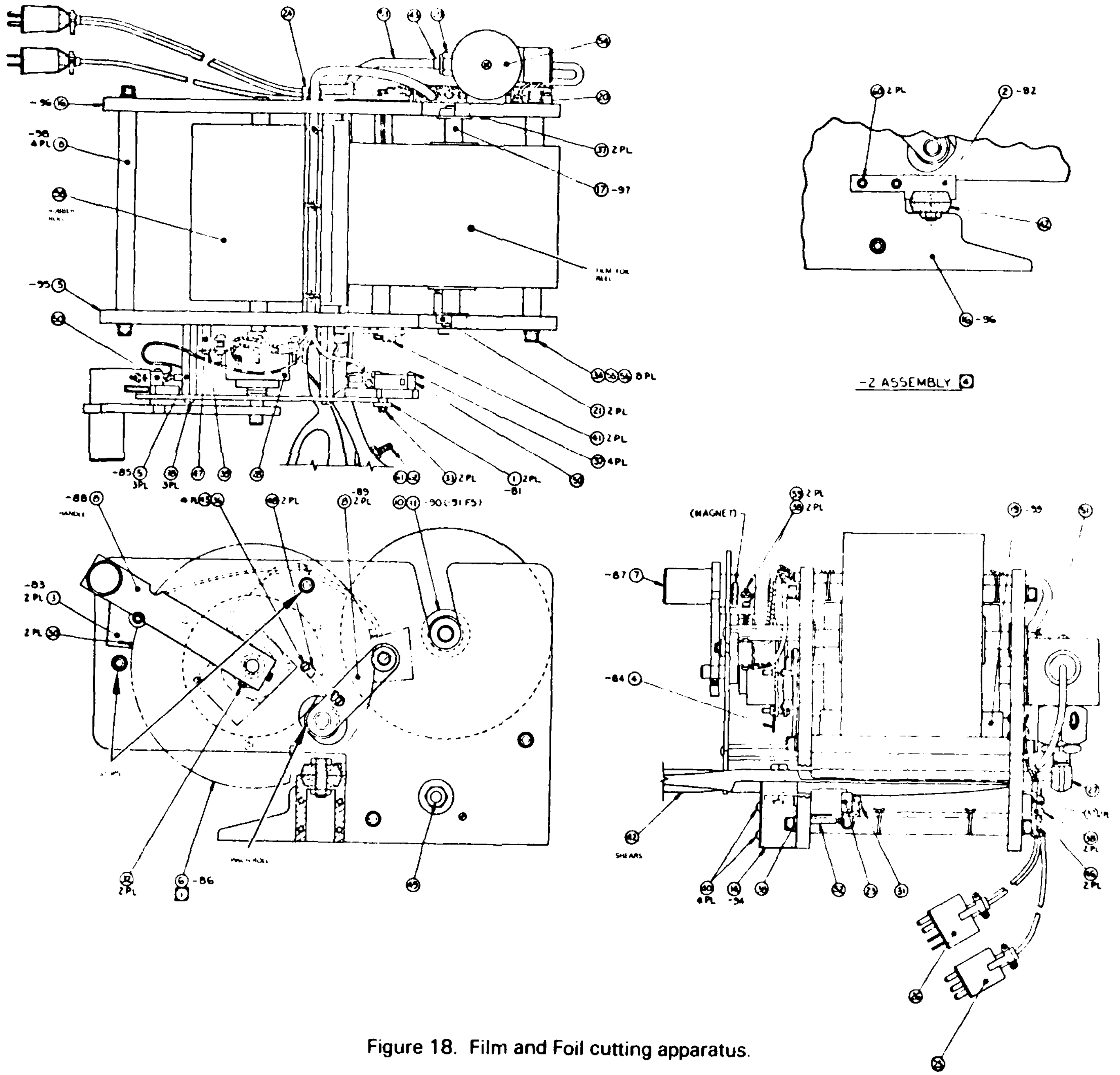

Figure 18. Film and Foil cutting apparatus.

discharge the film when it is pulled from the roll and a second unit to discharge the roll. Each unit consists of an F167 power supply and two shockless static bars type ME100.* Figure 19 shows the location of the deionizer for the film and the air jet.

Figure 19. Photograph of film and cutting apparatus showing location of air jet and deionizer.

The arrangement of the film and foil cutting apparatus is shown in Figure 20. It can be seen that three units are required: one for the Kapton shown on the left, one for the ground foil, and one for the line foil. A closeup view of the stacking fixture is shown in Figure 21.

In addition, a system interlocks the three film and foil cutting units to ensure that each layer of Kapton and foil is cut and then assembled in its proper sequence. Also, the number of layers of film and foil is required.

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*Manufactured by Simco Company, Inc., 920 Walnut Street, Lansdale, PA 19446.

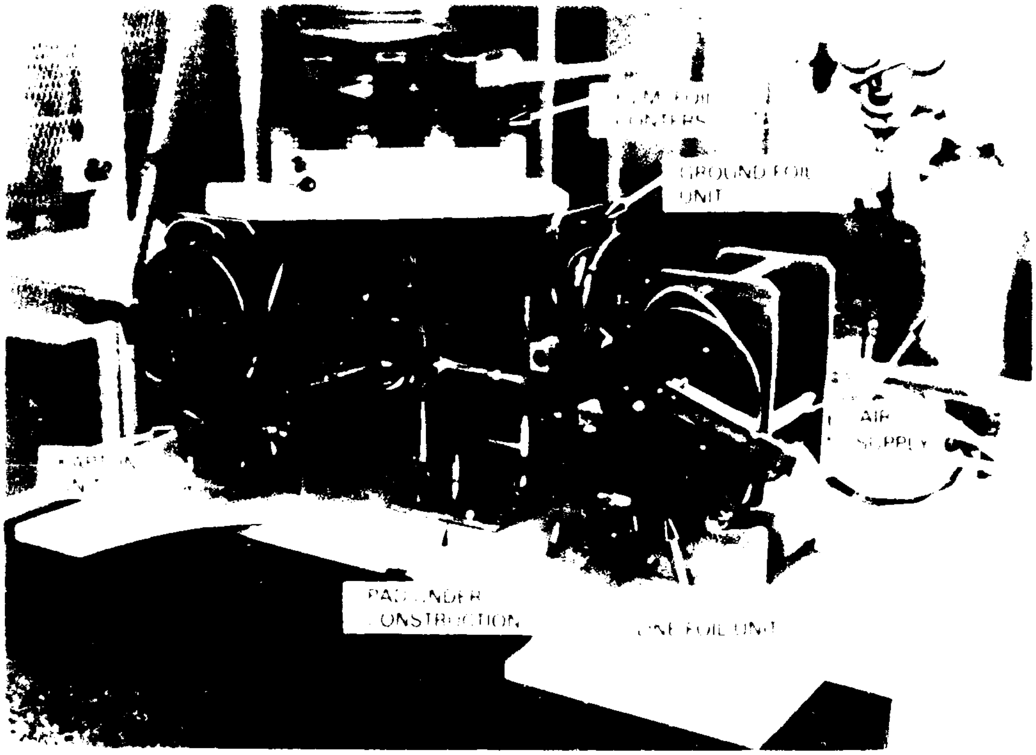


Figure 20. Photograph showing arrangement of the film and foil cutting apparatus.

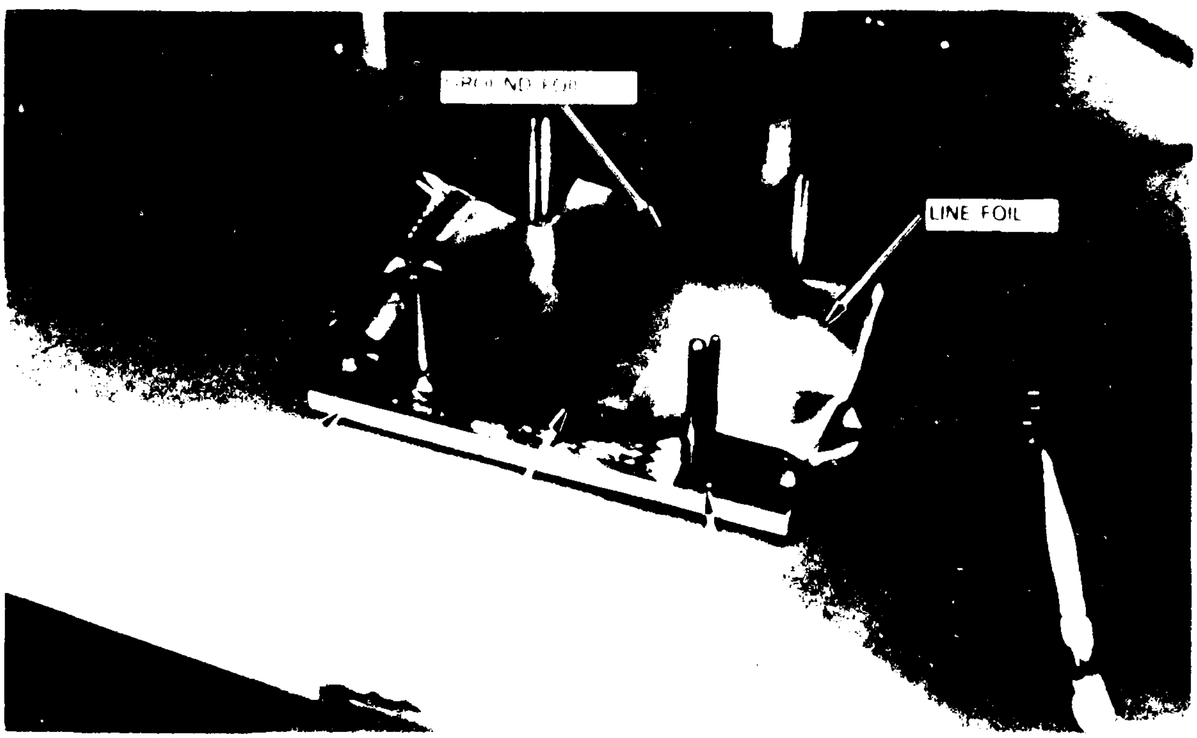


Figure 21. Stocking fixture

Since the total number of layers is large an automatic counter is mandatory. A schematic drawing of the interlock system is shown in Appendix I.

EXPERIMENTAL PAD ASSEMBLY

The first pad assembled utilized 0.5 mil (50 gauge) Kapton from material in stock to conserve the limited supply of 0.3 mil (30 gauge) Kapton film. The pad consisted of 500 layers each of Kapton film and aluminum foil for a total of 1,000 layers. Continuity tests after stacking indicated an intermittent short. The area of the short was identified by applying voltage to the capacitor with conduction of a large current through the short which burned the film around the short.

A new pad S/N 2 of identical construction was made and tested. It was lightly clamped and temperature cycled to 203°C. The test data are shown in Table 16. The dissipation factor (DF) at 1 kHz was much higher than expected. This was found to be due to faulty connections and measurement error. The measurements were made with a two-terminal bridge configuration rather than a four-terminal arrangement.

TABLE 16. HIGH TEMPERATURE ELECTRICAL MEASUREMENT OF 500 LAYER 0.5 MIL KAPTON CAPACITOR PAD S/N 2 IN VACUUM OVEN

TEMPERATURE, °C

	22	151	199	177	185	203	171	150	119	73	22
Capacitance, μF	5.9	4.75	4.76	4.71	4.71	4.72	4.71	4.71	4.71	4.72	4.73
Dissipation factor, %	9	7.8	7.1	16.7	17.2	19.3	17.5	17.2	16.6	15.8	14.8
Hours at temperature	-	16	6	71	18	4	1	2	17	23	-

After removing the pad from the vacuum oven the top plate was clamped tightly and both foils were clamped. The test data is shown below:

	Frequency, Hz	
	120	1000
Capacitance, μF	5.65	5.63
Dissipation factor, %	1.0	7.0

It can be seen that the capacitance has increased from 4.73 μF to 5.63 μF. The dissipation factor has decreased from 14.8 to 7 percent reducing the contact resistance by clamping the foils.

Continuity tests after clamping the pad indicated a short. The location was identified by applying a voltage with conduction of current through the short. This burned the shorted area. By limiting the current, the amount of burning was minimized and the particle that caused the short left intact and identified. The particle was metallic and presumed to be an aluminum fragment.

To reduce the number of particles affecting pad assembly the cutting and stacking equipment was moved into a clean room. The equipment was dismantled and thoroughly cleaned prior to starting S/N 3.

S/N 3 was identical to S/N 2 except the Kapton film was 0.3 mil thick. There were 500 layers each of Kapton and aluminum foil. Capacitance (C), dissipation factor (DF), and ratio of resistance to equivalent series resistance (R/ESR) were measured using an HP 4264 A LCR meter (bridge). The data are shown in Table 17a. However, the connections were faulty as can be seen by the high ratio of R/ESR. Measurements were made with both the two-terminal and four-terminal arrangement of the HP 4262 A LCR meter. More accurate measurements using a four-terminal arrangement and having good connections are given in Table 17b.

After making the above measurements the pad was tested for shorts with a continuity meter and appeared satisfactory. Upon applying voltage the unit broke down at 200 Vdc. Failure analysis indicated that the breakdown was caused by a small shard of aluminum. It appeared that the particle came from cutting the aluminum foil.

TABLE 17. ELECTRICAL MEASUREMENTS, S/N 3.
HP 4262A LCR METER

Bridge Configuration	C, μF 1 kHz	DF		R/ESR	
		120 Hz	1 kHz	120 Hz	1 kHz
	a. Faulty Connections				
2 - Terminal	10.29	0.051	0.379	6.4	5.99
4 - Terminal	10.01	0.050	0.374	6.1	5.74
	b. Good Connections				
4 - Terminal	10.41	0.005	0.019	0.8	0.28

The assembly of S/N 4 was started. The scheme was to stack 100 layers and test it for continuity and dielectric withstanding voltage of 400 Vdc for one minute. The first 100 layers tested satisfactorily; however, the second set of 100 layers failed after almost one minute at 400 volts. Unfortunately, the short destroyed the pad due to the large amount of stored energy.

Consequently, a more conservative approach was taken with the next pad. The plan was to make the assembly by separately stacking and testing 100 layer units. The units would be stacked one on top of the other; however, each unit would be tested individually first.

The assembly of S/N 5 was started. The first 100 layers tested satisfactorily at 400 Vdc for 1 minute. However, the second set of 100 layers failed at about 350 volts. The cause of the short could not be determined. It was assumed to be due to an aluminum particle.

Assembly of S/N 6 was started. The first 100 layers were tested at 400 Vdc for 1 minute and failed. Careful examination of the shorted areas showed three shorts due to aluminum fragments.

To be able to assemble a capacitor easily, it is apparent that the foil and film must be completely free of any particles. Therefore, an investigation to eliminate these particles was undertaken. Efforts were directed first to the cutting process itself, and secondly to persuading the manufacturers to improve their processing. The course of this effort is discussed the following section..

PARTICLES

Early in the program a problem of shorts was encountered that was traced to the shear foil cutting system of the foil dispensers. The shear cuts produced shards of aluminum that were carried over to the capacitor stack and punched through the Kapton. The use of work-hardened aluminum and a tearing process rather than shearing reduced the number of fragments considerably. Subsequently, it was discovered that there were foreign particles in both the Kapton rolls and the aluminum rolls as received from the manufacturers.

The means for eliminating the shards, fragments, and foreign particles are discussed in the remainder of this section.

Aluminum Particles

Failure analyses indicated that the shorts were caused by aluminum particles that came from cutting the foil. The aluminum is cut with a large pair of shears. Examination at a low magnification of the foil edge after cutting showed that the front edge, i.e., the edge next to the moving blade, was smooth and completely free of barbs or fragments. However, the back edge showed evidence of tiny barbs and some loose shards. These were easily visible at 10X magnification.

The aluminum foil used was Alloy 1145*. It is the standard alloy used in the manufacture of aluminum foil for paper and film wound capacitors. For these wound capacitor applications the foil is fully annealed after final slitting.

The manufacturer of the aluminum foil advised us that the fully annealed temper is difficult to cut and recommended that we use T19 temper (full hard)

*Manufactured by (Republic Foil) National Aluminum, Danbury, Connecticut.

for our application. A sample of Alloy 1145 T19 temper was obtained. For a trial the shears were carefully honed to a sharp edge. A number of cuts (~50) were made and carefully examined with a microscope at magnifications of 10X to 40X. Approximately two-thirds of the cuts exhibited no barbs or loose shards. The remaining one-third of the cuts showed one to three very small barbs which were firmly fixed. There were no loose fragments. The quality of these cuts was felt to be adequate for making stacked capacitors if further improvements could not be attained.

During the cutting experiments it was observed that it was possible to tear the aluminum foil quite easily, and furthermore the line of fracture was reasonably straight. Careful examination of a number of cuts (~60) made by this method did not reveal any barbs or fragments. At 40X magnifications the edges of all the fractures were perfectly clean. The tear can be controlled by clamping the foil or using a straight edge as a guide. The quality of these cuts was excellent and the pad assembly apparatus was modified to incorporate this method of cutting the foil. (Shears were retained for cutting the Kapton.)

Microtomes were installed in place of the shears for cutting the aluminum foil. Subsequently, there were more particles. These were traced to one of the microtomes which had been sharpened improperly and was dull. It was replaced by an X-acto blade which is used simply to nick and start the fracture of the foil. The other foil is fractured by tearing the foil against the microtome. Both methods work satisfactorily.

Particles in the Rolls

After eliminating the shards due to cutting the foil the problem persisted. It was discovered that the rubber drive rollers on the foil dispensers were collecting foreign particles from the aluminum foil.

A 10-foot length of foil was placed in a beaker and flushed with a spray of Freon. The run-off of Freon was then filtered and the trapped material in the filter was examined. The particles were metallic. It was evident that the contamination occurred during manufacture of the foil.

Samples from all of the foil and Kapton rolls were sent to the contamination control group for examination. The analysis consisted of taking

10 feet of material, rinsing it with alcohol, and counting the particles in 50 ml of the solution. The results for the foil are shown in Table 18. Table 19 gives the results for Kapton.

TABLE 18. PARTICLE ANALYSIS OF ALUMINUM FOIL. ALLOY 1145 T19 TEMPER 0.00017 INCH THICK. SAMPLE SIZE 2.9 FT^2

Sample Number	From	Average Number of Particles/Running Foot					
		Mils					
		0.2	0.4	1.0	2.0	4.0	8.0
A1	Middle	1149	1126			3	
A2	Middle	1059	674				
B1	Middle	977	594				
B2	Middle	1259	861			1	
C1	End	1180	686				
C2	End	820	438				
D1	End	1404	747				
D2	End	1178	454			1	
E1	End	945	364				
E2	End	1167	500				

TABLE 19. PARTICLE ANALYSIS OF KAPTON-H FILM. SAMPLE SIZE 3.1 FT^2 FROM MIDDLE OF ROLLS

Sample	Thickness, mil	Average Number of Particles/Running Foot					
		Mils					
		0.2	0.4	1.0	2.0	4.0	8.0
A1	0.5	529	912			1	
A2	0.5	480	380				
B1	0.3	810	1552			1	
B2	0.3	603	685		2		

It can be seen that there are many small particles and occasionally some large particles. The small particles are one to two times the film thickness and the large particles nearly 20 times the size of the film.

Obviously, many of these particles are large enough to puncture the Kapton when pressed and cause shorts.

PAD TEST APPARATUS

During assembly of the first experimental pads, each 100 layers were tested for shorts at 400 Vdc. The procedure of stacking, compressing 100 layers, and testing each group of layers proved ineffectual. This was due primarily to trying to compress the pad with a C-clamp, which twisted the stack and misaligned the layers. In addition, the assembly operation and testing were carried out in separate laboratories.

To eliminate these problems, a fixture was designed for clamping and applying voltage. After stacking a number of layers, the base plate is placed in the fixture. An air cylinder is used to compress the pad to a fixed pressure. The pad then can be connected to a power supply with spring clips attached to the side of the fixture. A photograph of the test fixture with a pad (S/N 7) in position for test is shown in Figure 22. Detailed drawings of the test fixture are given in Appendix J. A schematic diagram of the power supply is given in Appendix K.

PROTOTYPE CAPACITOR ASSEMBLY

Much was learned while assembling the experimental pads (S/N 1-6). The film and foil cutting apparatus was developed successfully. The stacking of the layers turned out to be straightforward. The shears for cutting the foil were replaced and a new method of tearing the foil was installed to eliminate the aluminum shards due to cutting. A test fixture was developed for compressing and testing the pad after laying up a number of layers.

Although particles in the rolls were still a problem, it was felt that a larger pad of 22 μF should be assembled to verify the assembly procedures. This would be followed by the fabrication of a 45 μF prototype capacitor.

The dielectric for S/N 7 was 30 gauge (0.0003 inch) Kapton 3.75 inches wide. The foil was 0.00017 inch thick hard aluminum 3.5 inches wide. The

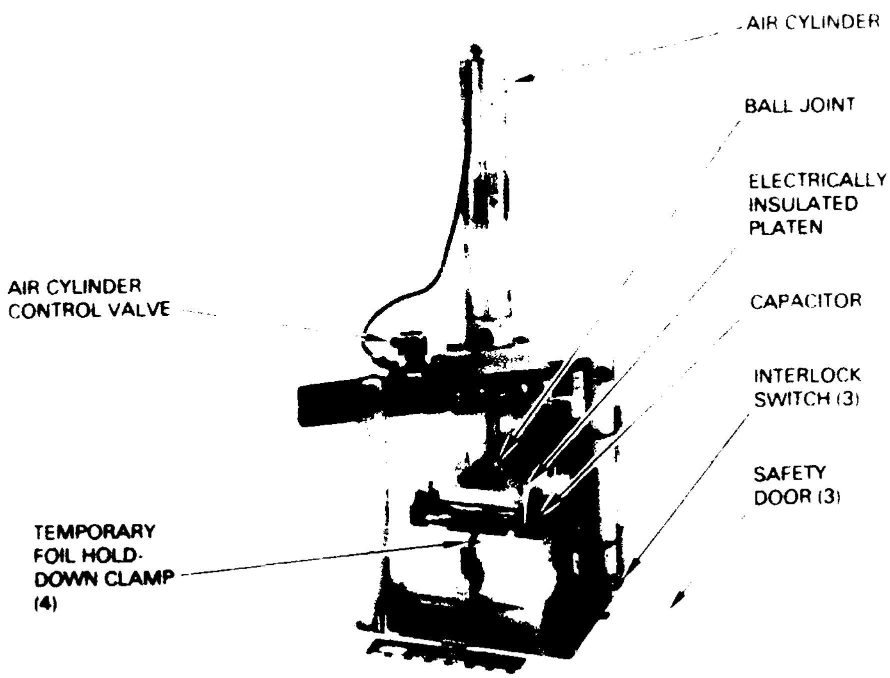


Figure 22. Front view of test fixture for compressing pad during assembly.

active dielectric dimensions therefore were 3.5 x 3.5 inches. Using the method of intermittent stacking and testing described above, a pad of 1300 pieces of Kapton and 1301 foils was assembled. The capacitance was 22.5 μF.

The stack was tested every 200 layers for a total of six basic tests. Numerous shorts necessitated unstacking and restacking with secondary tests to attain 22.5 μF.

A closeup photograph of the stack is shown in Figure 23. The stack has shifted to the right due to the reworking. Figure 24 is a photograph of the stack viewed from the ground foil side. The stack, in general, is well-centered between the steel alignment pins. Due to the misalignment, it was necessary to modify the pressure plate slightly to compress the stack evenly.

The capacitance measured 23.6 μF and the D.F. 0.016 at 1000 Hz.

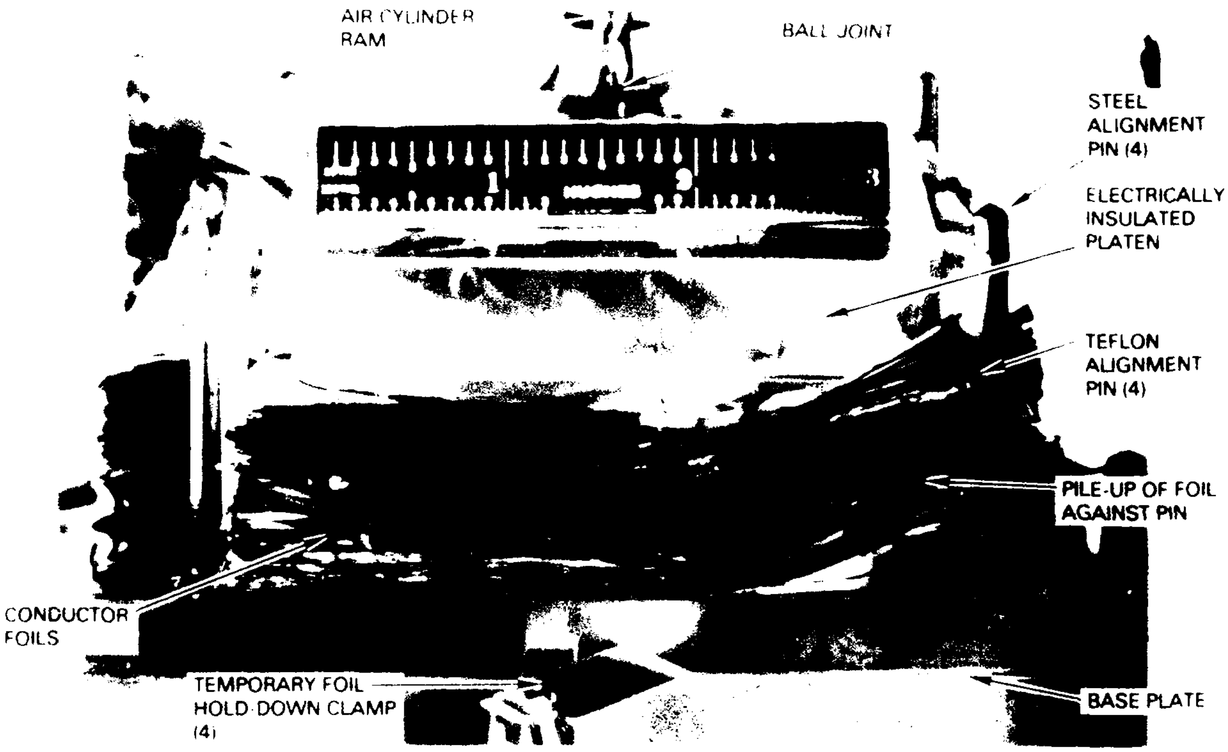


Figure 23. Closeup View of Capacitor Stack (S/N7) in Compression Test Fixture. View is From Conductor Foil Side.

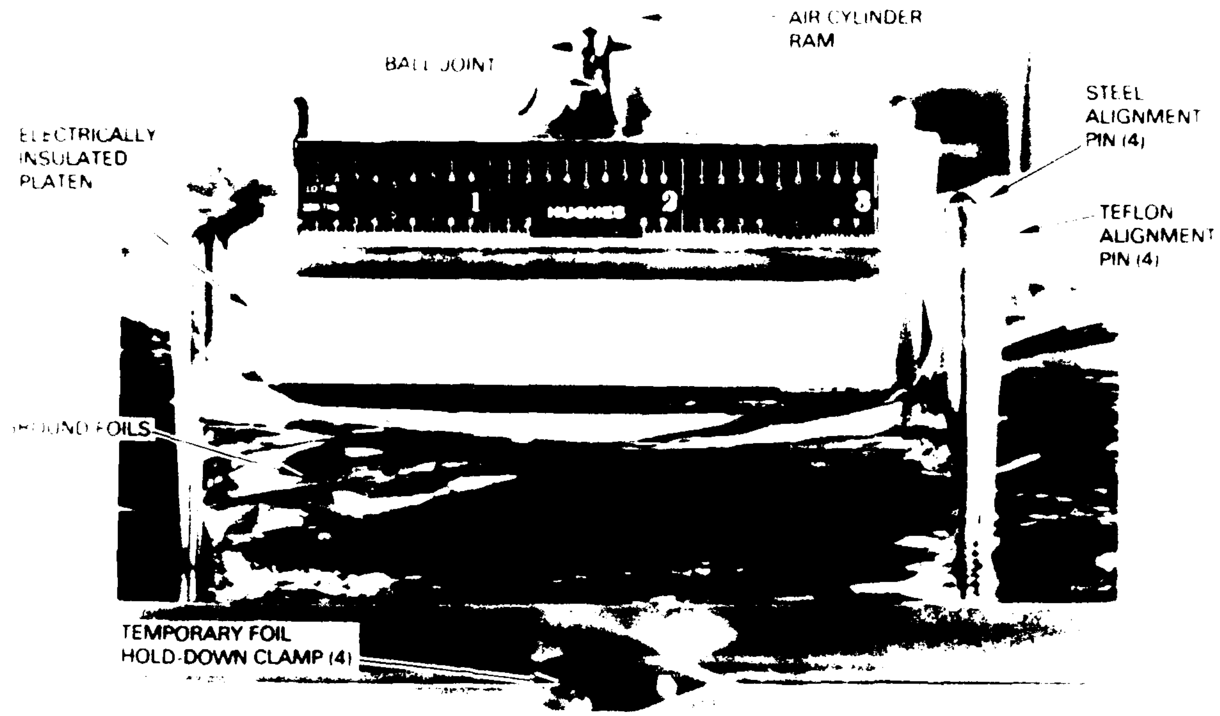


Figure 24. Closeup View of Capacitor Stack (S/N7) in Compression Test Fixture. View is from Ground Foil Side.

The capacitor was placed in a vacuum oven and temperature cycled to 200°C. A summary of the test data is shown in Table 20. After removing the capacitor from the vacuum oven, the top plate was loose. This was attributed to removal of the air from between the layers of film. After tightening the top plate, the capacitance was 25.9 μF.

The dissipation factor obviously was very high. Tests showed that the line foil connection was inadequate, while the ground foil connection was satisfactory. The difference between the two clamps can be seen in Figure 25. Holes were drilled through the foil for the ground connection, whereas the bolts used to clamp the line foils were on the outside.

After changing the line foil connections the capacitance was 25.9 μF and the dissipation factor 0.001.

TABLE 20. HIGH TEMPERATURE ELECTRICAL MEASUREMENTS OF 1300 LAYER 0.5 MIL KAPTON CAPACITOR S/N7 IN VACUUM OVEN

TEMPERATURE, °C

	21	110	142	170	200	200	171	145	112	21
Elapsed Hours	0	21	24	43	48	163	167	183	189	257
C, F	23.4	22.7	23.2	23.6	23.9	23.8	23.8	23.8	23.9	23.9
D.F., %	1.6	2.2	2.8	3.1	3.9	4.3	4.1	4.0	3.9	7.3

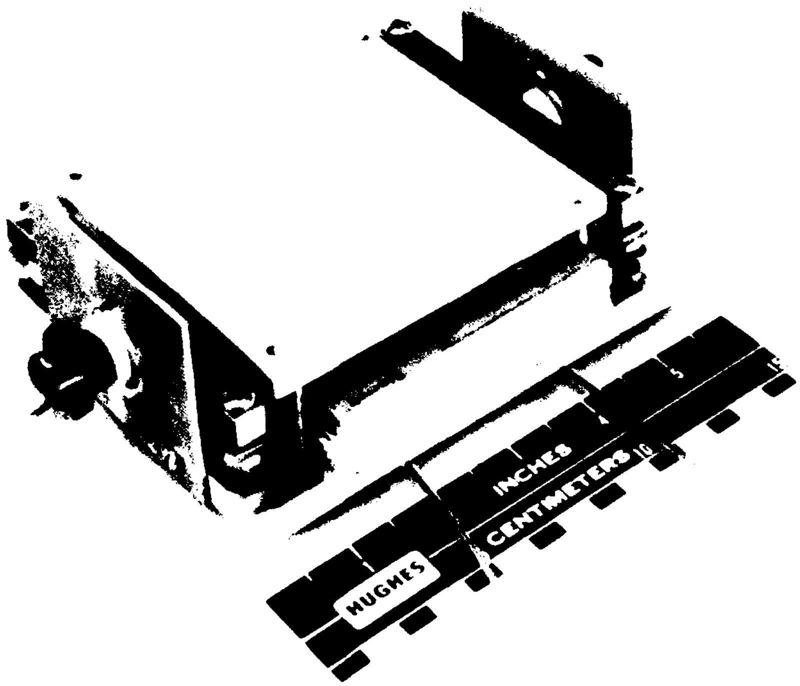


Figure 25. Capacitor assembly, S/N 7.

Many of the shorts were the Kapton film quality. The 30 gauge Kapton is extremely thin. It has some pinholes and thin spots. Particles in both the Kapton and foil rolls contributed to the breakdowns and shorts too.

Therefore, it was decided to use heavier film for S/N 8. The dielectric strength of 50 gauge (0.0005 inch) Kapton is higher than the 30 gauge. This can be seen by comparing the critical test voltages used by Du Pont, shown in Table 9, for the same number of survivors, e.g., 500 volts for the 50 gauge film compared to 300 volts for 30 gauge. In addition, small particles should be less damaging with heavier film.

The construction of S/N 8 was identical to S/N 7, except 50 gauge Kapton was used instead of 30 gauge. Foil and film that showed any evidence of particles, holes, or thin spots was discarded. The pad was tested every 100 layers at 400 Vdc. No shorts were found. The capacitance was measured at 1,100 layers in order to estimate the total number of layers needed. However, it was not possible to obtain a steady reading due to poor contact to the foils. Calculations suggested that 3,500 layers should be around 45 μF and stacking was terminated at that point.

The pad is shown in the test fixture in Figure 26.

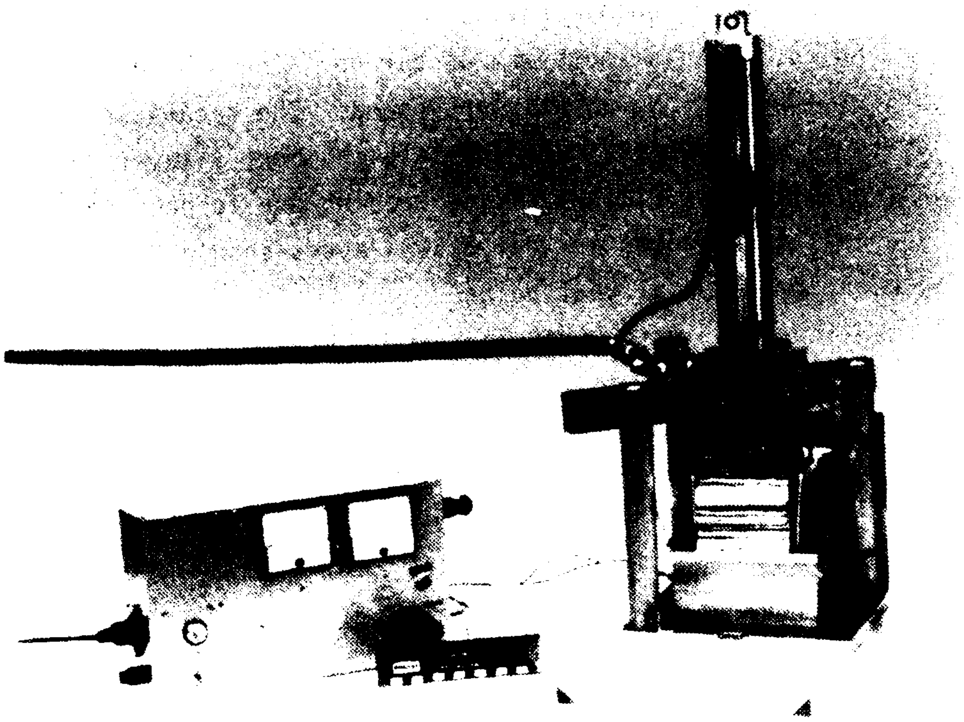


Figure 26. Capacitor pod S/N 8.

VII. PROGRAM SUMMARY AND RECOMMENDATIONS

MATERIAL DEVELOPMENT

Three candidate materials with suitable properties were investigated. These were Kapton-H, mica paper, and Teflon. Teflon has good properties for this application. The dissipation factor is very low and the upper temperature limit adequate. Unfortunately Teflon cold flows, i.e., flows under pressure, and hence was considered unsuitable for this application. Teflon has an extremely low coefficient of friction and would be hard to keep in place, especially during shock and vibration.

Mica paper is an all-mica insulating paper made from mica flakes. No binder is used. It has a very high temperature limit. For this application mica paper was to be used unimpregnated, since the electrical stress was very low. To evaluate the mica paper a number of capacitors were wound and tested. The results were compared with identical Kapton capacitors. The mica paper capacitors exhibited excessive leakage current, which was attributed to moisture. After drying, the leakage current decreased to a satisfactory value. Surprisingly, the measured capacitance was very small. This was a result of the large amount of air between the many layers. It appeared that mica paper could not be used unimpregnated. Impregnation would complicate the design and assembly; it would also require extensive additional evaluation. Therefore, mica paper was not considered further as a candidate material.

The operating temperature of Kapton is limited by its dissipation factor. The dissipation factor reaches a minimum at about 200°C and then increases rapidly. Kapton can be used for this application, if the heat conduction is sufficient to limit the hot-spot temperature to about 230°C. Electrical measurements of the wound capacitors agreed substantially with the Du Pont specifications.

It is evident that, of the candidate materials, Kapton was the logical choice to be used for the capacitor designs.

The two foils considered for use were aluminum and copper. A review of their properties indicated that aluminum was the preferred foil material. Aluminum has the lowest mass resistance, it is chemically nonreactive with other candidate materials, and it can be welded or mechanically joined to provide joints of low electrical resistance.

CAPACITOR DESIGNS

To meet the goals of this program, a new capacitor design was required. The design first must manage the internal dielectric heat and conduct it efficiently to the outside. The hot-spot temperature must be less than the upper limit of the dielectric material when the ambient is 200°C. Kapton was considered adequate to meet these goals.

The proposed design was for a single capacitor pad made up of alternate sheets of Kapton and aluminum foil. One-half of the aluminum foils are clamped together and connected to the bottom of the case, which is in intimate contact with the 200°C cold plate.

The 45 μF capacitor design is based on using 0.0003 inch Kapton, 3-3/4 inches wide, with aluminum foil 0.00017 inches by 3-1/2 inches wide. The margins are 1/8 inch. The number of layers required is 2155. The overall case dimensions are 5.9 x 5.4 x 3.4 inches.

The 180 μF capacitor design is similar to the 45 μF capacitor design, but larger. The design is based on using 0.0003 inch Kapton, 4-1/2 inches wide, with aluminum foil 0.00017 inches by 4-1/4 inches wide. The margins are 1/8 inch. The number of layers required is 5870. The overall case dimensions are 6.62 x 6.12 x 5.50 inches.

The case to enclose the capacitor (pad) consists of a base, a cover, and two terminal endplates, all made from 6061-T4 aluminum alloy and welded together. The capacitor is attached to the base which serves as a heat-sink path. The line foils are connected to the terminal endplate feed-throughs and the grounded foils are attached to the base.

To prove the design a prototype case was fabricated. To ensure that the capacitor will not be overheated during welding, the maximum base plate temperature was measured. A plot of the temperature profile showed that the heat from welding is dissipated effectively. The temperature of the base plate near the capacitor during welding will be less than 149°C, well below the operating temperature of 200°C.

TEST PLAN

A capacitor test plan was prepared to provide the test procedures; it describes the performance tests to be performed for both types of capacitors. These tests will establish the electrical characteristics of the capacitors. Performance capabilities will be determined under limited environmental conditions. Burn-in tests and life tests at 200°C will demonstrate that the design is suitable for high temperature operation. Capacitor pads will be inspected during manufacture; acceptance tests of the complete encased capacitor assembly will follow.

ASSEMBLY EQUIPMENT

The first equipment made was for cutting the film and foil to size. The base of the capacitor served as a stacking fixture. The apparatus dispenses a set amount of film or foil which can be cut off and stacked to form the capacitor.

The equipment comprises three separate units, one for the Kapton and two for the aluminum foils. Each unit consists of a roll of aluminum or Kapton material and a large rubber-covered supply roll. The film or foil is held against the supply roll by a spring-loaded pinch roll. When the rubber roll is rotated, it pulls the film or foil from the reel. Stops control the amount of material dispensed. The material is then cut off with shears and conveyed to the stacking fixture. The three units are interlocked to ensure that each layer of Kapton and foil is cut and then assembled in its proper sequence. Counters provide the total number of layers.

During assembly of the first experimental pads each 100 layers was tested for shorts. The C-clamp used for compressing the stack tended to twist the

stack and misalign the layers. A fixture was designed for clamping and applying voltage to eliminate this problem. An air cylinder is used to compress the pad to a fixed pressure. The pad is then connected to the power supply.

EXPERIMENTAL PADS

The experimental pads were used to develop the procedures and processes needed. The first pad assembled consisted of 500 layers each of 0.5 mil Kapton and aluminum foil. Continuity tests after stacking indicated an intermittent short. The next pad (S/N 2) was of identical construction. It was lightly clamped and heated in a vacuum oven to 203°C for 4 hours successfully. After removing the pad from the vacuum oven, continuity tests indicated a short. Investigation proved that the short was caused by an aluminum fragment.

S/N 3 was identical to S/N 2 except that the Kapton film was 0.3 mil thick. There were 500 layers each of Kapton and aluminum foil. The capacitance was 10.41 μF and the dissipation factor 0.019. Upon applying voltage the unit broke down at 200 VDC. Failure analysis indicated the cause of the breakdown resulted from a small shard of aluminum from cutting the foil.

Beginning with the next pad, each 100 layers would be tested at 400 VDC individually during stacking. The next three units failed at 100 to 200 layers. All the shorts were attributed to aluminum fragments from the cutting operation.

Obviously, the foil and film must be completely free of any particles if capacitors are to be assembled successfully. Therefore, an investigation to eliminate these particles was undertaken.

PARTICLES

The problem of shorts in the first pads was traced to the shear foil cutting system. The shear cuts produced shards of aluminum that were carried over to the capacitor stack and pierced the Kapton. Substituting hard temper foil for annealed aluminum, and using a tearing rather than a shearing process, reduced the number of particles.

After eliminating the shards caused by cutting the foil, problems with shorts persisted. It was discovered that there were aluminum particles in the rolls. This contamination occurred during manufacture of the foil. Analyses of all of the rolls of foil showed several hundred 0.4 mil particles per foot and a few particles as large as 1.0 mil. Obviously, many of these particles are large enough to puncture the Kapton.

The situation with the Kapton rolls was similar. There were many small non-metallic particles and a few particles as large as 1.0 mil.

PROTOTYPE PADS

Much was learned during assembly of the six experimental pads. The film cutting apparatus was developed successfully. A new method of cutting the foil replaced the shears. A test fixture was developed for compressing and testing the pad during assembly. At this point assembly of the prototype pads began.

The first pad (S/N 7) consisted of 1300 layers of 0.0003 inch Kapton 3.75 inch wide. The foil was 0.00017 inch thick hard aluminum. The active dielectric dimensions were 3.5 x 3.5 inches. The capacitance was 23.6 μF and the dissipation factor 0.016. The pad was heated in a vacuum at 200°C for 115 hours. After the test, removal of the air between the layers had loosened the top plate. After recompressing the stack and correcting faulty line terminations, the capacitance was 25.9 μF and the dissipation factor was 0.001.

During assembly the stack was tested every 200 layers. Numerous shorts were attributed to particles in the foil rolls and to the Kapton film quality. The 30-gauge (0.0003 inch) Kapton is extremely thin, with some pinholes and thin spots.

Therefore, it was decided to use heavier film for the remaining capacitors. The dielectric strength of 50 gauge (0.0005 inch) Kapton is higher than 30 gauge film. Also, small particles should be less damaging to heavier film.

The construction of S/N 8 was identical to S/N 7 except that 50 gauge Kapton was used instead of 30 gauge. Foil or film that showed any evidence of particles or irregularities was not used. The pad was tested every 100 layers; no shorts were found. The number of layers required for 45 μF was estimated and stacking terminated at 3500 layers. After the terminations are completed the capacitor will be tested.

REMAINING WORK

The work remaining is to complete the capacitor fabrication of Phase II and to carry out the Phase III tests. The fabrication will continue with the 45 μF assembled capacitors only per agreement with the AF project monitor.

S/N 7 will be tested at low temperatures and cycled to 200°C to check the integrity of the compression of the capacitor. Finally, it will be tested for dielectric withstanding voltage.

Starting with S/N 8 the capacitors will be incased and tested per the Test Plan.

ACCOMPLISHMENTS

- Kapton selected as dielectric material
- Design of capacitor capable of 200°C operation completed
- Equipment designed for cutting film and foil
- Test equipment made for compressing and testing pads during assembly
- Particles due to cutting foil were eliminated
- Unpowered tests at 200°C completed successfully
- First 45 μF capacitor pad completed.

RECOMMENDATIONS

It is recommended that 50 gauge film be used for the remaining capacitors. The heavier film has higher dielectric strength and will suffer less damage from small particles.

Two types of capacitors, 45 μF and 180 μF, were specified. The two capacitors are identical except in size. It is suggested that, for economy, effort should be concentrated wholly on producing 45 μF capacitors.

The early problem with shorts traced to the shears used for cutting the foil was eliminated by modifying the cutting method. Discovery of shorts caused by foreign particles in both the Kapton and aluminum rolls as received from the manufacturers indicate clearly that it will be necessary to work with the manufacturers to try to obtain cleaner Kapton and aluminum foil.

It is expected that somewhat cleaner material can be obtained, but it is unlikely that it will be clean enough. Further cleaning will be necessary, probably solvent washing and drying in a clean environment. This technology is already being used for audio and video tape and should be adapted for this application.

Use of thinner Kapton is attractive to reduce the size and weight of the capacitor. However, the dielectric strength of 30 gauge Kapton is inadequate due to thin spots and pin holes. The film should be tested before being used. This can be done using the same methods employed for metallized film.

For better producibility and reduced manufacturing costs, the assembly process should be automated. This will require designing equipment for handling and stacking the film and foil. A number of options are available to do this with a minimal development effort.

APPENDIX A

DESCRIPTION/SPECIFICATIONS
ADVANCED CAPACITOR DEVELOPMENT

ADVANCED CAPACITOR DEVELOPMENT

1.0 OBJECTIVE

The objective of this effort is to design, develop, and fabricate AC filter capacitors for airborne applications which have a higher operating temperature than presently available. A secondary objective is to reduce the size and weight of these capacitors.

2.0 SCOPE

2.1 This effort includes the following: 1) Development of suitable capacitor materials, 2) Preliminary capacitor design effort, 3) Final design effort, 4) Capacitor fabrication, 5) Capacitor testing, and 6) Reporting. The program shall be accomplished in the distinct phases identified below. The time periods in parentheses are Air Force estimates of the times required to accomplish each phase. Phase III includes reporting.

Phase I - Design (10 months)
Phase II - Capacitor Fabrication (14 months)
Phase III - Tests (9 months)

2.2 A capacitor pad shall be defined as that element of capacitor construction consisting of alternating layers of conducting foil and dielectric medium, which stores electrical energy. In a given capacitor, several pads may be connected in series/parallel configurations to obtain the desired performance characteristics. However, capacitors consisting of a single pad are not prohibited from consideration.

3.0 GENERAL BACKGROUND

3.1 INTRODUCTION The AC power systems of aerospace vehicles typically operate at 400 Hz, at an output voltage rating of 120 VAC. Capacitors are used in these systems as filters to remove extraneous frequencies. At the present, AC filter capacitors tend to constitute a significant portion of a total generator system weight (approximately 20%). The operating temperature limit of the generator system is greatly impacted by the operating temperature limit of the filter capacitors. Thus a higher capacitor operating temperature would significantly improve the performance of the total generator system. Present day production capacitors cannot satisfy the envisioned thermal requirements of future Air Force missions. In addition, a reduction in the size and weight of these capacitors is highly desirable.

3.2 MATERIALS Dielectric materials now used in capacitors are polymer plastics, such as polysulfone and polycarbonate, with operating temperature film limitation of 135°C. This film limitation is unacceptable for supersonic persistance aircraft where conditions indicate a film temperature of 200°C or higher is required. Improved capacitor technology will significantly reduce the weight of

the generator cooling system. In addition, increases in the Mean Time Between Failures (MTBF) and improvements in overall capacitor performance, will be realized.

3.3 THERMAL MANAGEMENT Contemporary capacitor systems do not adequately deal with the problem of thermal management. Though the preferred method of fabricating capacitors consists of tightly winding alternating layers of dielectric, kraft paper, and metal foil, the scheme lends itself to poor thermal control, poor impurity control, and poor manufacturing control in regard to design specifications. Improved thermal management is essential to achieving higher temperature performance.

3.4 PREVIOUS PROGRAM For several years, the Aero Propulsion Laboratory has invested in programs aimed toward improving overall capacitor performance. Areas of improvement emphasized were dielectric strength, dielectric temperature, capacitor design, and capacitor fabrication techniques. The primary objective of these earlier programs was the reduction in size and weight of high power pulsed capacitors. The most recent of these (contract F33615-79-C-2081, Hughes Aircraft Corporation, El Segundo, CA) has achieved improved capacitor performance by refinements in capacitor design and fabrication techniques. An interim report ("Advanced Capacitors," AFWAL/TR-82-2098, November 1982) describes the results of a portion of this effort.

4.0 GENERAL TECHNICAL TASKS/SPECIFICATIONS

The technical requirements of this Description/Specification are defined in this paragraph. The effort shall be accomplished in the consecutive phases identified below. Two capacitor sizes shall be developed and tested: a 180 and a 45 microfarad capacitor. Each capacitor shall be designed to meet the requirements of Addendum #1 to this Description/Specification. Physical size, weight, and cost estimates of each capacitor value shall be made for a possible production run of these capacitors employing the technology developed in this program. The capacitors fabricated in this program shall be shipped to AFWAL at the completion of this program for performance testing at AFWAL facilities.

4.1 PHASE I - CAPACITOR DESIGN

The capacitor Design Phase shall be broken into the three tasks identified below. Written approval of the Air Force Procurement Contracting Officer is required prior to contractor initiation of Phase II.

4.1.1 MATERIALS DEVELOPMENT - The contractor shall identify promising existing material candidates and/or recommend generic types of materials which are suitable for capacitor dielectric systems. The contractor shall consider material properties such as dielectric constant, dissipation factor, dielectric strength, corona, ease of manufacture and handling, variation in properties with temperature and frequency, cost and susceptibility to pinholes and thickness variation.

4.1.1.1 From the identified material candidates the contractor shall propose several dielectric systems suitable for the requirements specified in Addendum #1 to this Description/Specification. For each of the proposed dielectric

systems, the contractor shall estimate the average dielectric constant, average dielectric stress, and the maximum operating temperature if used in a capacitor pad.

4.1.1.2 Materials classified as polychlorinated biphenyls (PCBs) shall not be considered for use in this program.

4.1.1.3 In the modification or development of any material, the contractor shall consider compatibility of this material with other materials of the capacitor (i.e.; films, impregnants, papers, and foils).

4.1.2 PRELIMINARY DESIGN - This task shall encompass design to approximately 50% completion for both capacitors (Addendum #1). A design review shall be held at the contractor's facility after completion of this task. At this time the Air Force will review both the technical and financial aspects of the program. Contractor shall present preliminary drawings of work performed in this task. Long lead materials for Phase II shall also be identified at this design review. Air Force approval shall be required prior to contractor purchase of these materials (CDRL Seq #7).

4.1.3 FINAL DESIGN - This task shall encompass completion of system design. A design review shall be held at W-PAFB, Ohio, upon completion of this task. At this time the Air Force will again review the program. In addition, sketches shall also be presented describing packaging concepts for a possible production run. Temperature range, weight, and volume for the production application of each capacitor shall be projected. Contractor shall discuss in detail the completed final drawings for each capacitor (CDRL Seq #7).

4.2 PHASE II - CAPACITOR FABRICATION

Twenty-five complete capacitors of the 180 microfared size and twenty-five complete capacitors of the 45 microfared size shall be fabricated during this phase as designed in Phase I. Test procedures describing the performance tests to be performed for both types of capacitors shall be developed during this phase, incorporating applicable electrical performance tests as specified by Addendum #1 to this Description/ Specification (CDRL Seq #5).

4.3 PHASE III - TESTS

This phase shall encompass the formal testing of the assembled capacitors. The tests shall be performed in accordance with the Air Force approved test procedures (paragraph 4.2). Contractors shall perform a failure analysis on any capacitor which does not successfully complete testing. Within this failure analysis, the contractor shall identify the causes of failure and determine possible methods to prevent its recurrence. The contractor shall document this phase of the program (CDRL Seq #6).

4.4 ADDITIONAL REQUIREMENTS

4.4.1 DESIGN TO COST - Design, manufacturing methods and materials for each size of capacitor shall be such as to yield capacitors suitable for Laboratory use. However, the contractor shall establish an effort to ensure that the capacitor designs can be economically manufactured should the technology evolve into production hardware. No more than 80 total technical person hours shall be allocated to this effort.

4.4.2 QUALITY ASSURANCE - Each capacitor designed, fabricated and tested for this program shall incorporate features that will enable it to meet the general specifications of MIL-C-83421. The workmanship utilized to fabricate the capacitors shall be such as to yield a trouble free test program both at the contractor's facility and at AFWAL's Facility. (AFWAL will perform testing on the hardware after the contract is completed.)

4.4.3 SYSTEMS SAFETY - The contractor shall fully assess the hazards of testing each capacitor size. Of primary concern are the following: capacitor containment during high temperature tests and electric shock hazards typically associated with electric testing (CDRL Seq #12).

4.4.4 RELIABILITY AND MAINTAINABILITY - From the design phase, fabrication phase, and through the testing phase of each capacitor, consideration shall be given to the factor of reliability and maintainability. However, no extensive reliability testing program shall be under taken as part of this effort. Nonetheless a prediction of the degree of reliability and maintainability shall be determined based on the techniques used to design and fabricate similar devices (CDRL Seq #11).

5.0 DATA AND PRESENTATIONS

5.1 DATA

Data shall be solely in accordance with the DD 1423.

5.2 PRESENTATIONS (CDRL Seq #9)

5.2.1 PHASE I - PRELIMINARY DESIGN - The contractor shall give a formal presentation in conjuction with the preliminary design review (4.1.2)

5.2.2 PHASE I - CRITICAL DESIGN - The contractor shall also give a formal presentation in conjunction with the final design review (4.1.3).

5.2.3 PHASE III - FINAL PROGRAM - Finally, a formal presentation shall be given at the completion of the program. This presentation shall be a summary, covering all three phases, and be given at W-PAFB, Ohio.

APPENDIX B

ADDENDUM #1 TO SECTION C - DESCRIPTION/SPECIFICATIONS

ADDENDUM #1 TO SECTION C - DESCRIPTION/SPECIFICATIONS
DETAILED SPECIFICATION
180-Microfarad Capacitor
45-Microfarad Capacitor

1.0 SCOPE

1.1 SCOPE. THIS DOCUMENT COVERS THE DETAILED REQUIREMENTS FOR PLASTIC FILM DIELECTRIC, FIXED CAPACITOR, HERMITICALLY SEALED IN AN ELECTRICALLY GROUNDED METAL CASE.

2.0 APPLICABLE DOCUMENTS

2.1 APPLICABLE DOCUMENTS. THE FOLLOWING DOCUMENTS, OF THE ISSUE IN EFFECT ON THE ISSUE DATE OF THIS DRAWING, FORM A PART OF THIS DOCUMENT TO THE EXTENT SPECIFIED HEREIN.

SPECIFICATION

MILITARY

MIL-C-83421A CAPACITORS, FIXED, SUPERMETALLIZED PLASTIC FILM DIELECTRIC, DC AND AC HERMETICALLY SEALED IN METAL CASES, ESTABLISHED RELIABILITY, GENERAL SPECIFICATION FOR

STANDARDS

MILITARY

MIL-STD-202F TEST METHODS FOR ELECTRONIC AND ELECTRICAL COMPONENT PARTS

MIL-STD-220A METHOD OF INSERTION - LOSS MEASUREMENT

MIL-STD-1285 MARKING OF ELECTRICAL AND ELECTRONIC PARTS

3.0 DESIGN REQUIREMENTS

3.1 DETAILED REQUIREMENTS. CAPACITORS SHALL BE DESIGNED TO MEET ALL ELECTRICAL AND MECHANICAL REQUIREMENTS OF MIL-C-83421A FOR FAILURE RATE M, IN ADDITION TO THE REQUIREMENTS LISTED HEREIN.

3.1.1 METALS. ALL METALS, WHEN USED, (UNLESS OTHERWISE SPECIFIED HEREIN), SHALL BE CORROSION-RESISTANT TYPES OR TREATED TO RESIST CORROSION. DISSIMILAR METALS SHALL NOT BE USED IN INTIMATE CONTACT WITH EACH OTHER UNLESS SUITABLY FINISHED TO RESIST ELECTROLYTIC CORROSION. CURRENT CARRYING PARTS SHALL BE NONFERROUS, EXCEPT FOR TERMINALS FORMING PART OF A METAL-TO-GLASS SEAL, AND THE CASE.

3.1.2 QUALITY CONFORMANCE INSPECTION. SHALL BE PERFORMED AS SPECIFIED HEREIN.

3.2 DESIGN AND CONSTRUCTION. THE DESIGN AND CONSTRUCTION SHALL BE IN ACCORDANCE WITH THE REQUIREMENTS SPECIFIED HEREIN.

3.2.1 CAPACITOR ELEMENTS. THE CAPACITOR ELEMENTS SHALL BE CONSTRUCTED SO AS TO MAXIMIZE THERMAL STABILITY WHILE MINIMIZING SIZE AND WEIGHT.

3.2.2 CONSTRUCTION. THE 180 MICROFARAD CAPACITOR ELEMENTS SHALL BE ASSEMBLED ON EITHER SIDE OF A FEEDTHROUGH BUS. THE INTERNAL CONDUCTOR TABS SHALL BE LOCATED AND CONNECTED APPROPRIATE FOR MINIMUM INDUCTANCE BETWEEN THE FEEDTHROUGH BUS AND THE METAL CASE ELECTRICAL GROUND. THE 45 MFD CAPACITOR ELEMENTS SHALL BE ASSEMBLED IN A NON-FEED THROUGH MANNER, WITH BOTH TERMINALS ON ONE SIDE OF THE CAPACITOR CASE.

3.2.3 CASE. EACH CAPACITOR SHALL BE ENCLOSED IN A HERMETICALLY-SEALED METAL CASE WHICH WILL PROTECT THE CAPACITOR ELEMENT FROM MOISTURE AND MECHANICAL DAMAGE UNDER ALL TEST CONDITIONS SPECIFIED HEREIN. THE END SEALS SHALL BE GLASS-OR-CERAMIC-TO-METAL.

3.3 <u>ELECTRICAL CHARACTERISTICS</u>

3.3.1 RATING.

3.3.1.1 VOLTAGE. 150 VRMS, MAXIMUM.

3.3.1.2 FREQUENCY. 400 HZ.

3.3.1.3 CAPACITANCE. 180 MFD AND 45 MFD ±10% WHEN MEASURED AS SPECIFIED IN 4.3.2, FROM EITHER, OR BOTH TERMINALS TO CASE AT +25°C.

3.3.1.3.1 CAPACITANCE CHANGE. MAXIMUM CAPACITANCE CHANGE SHALL BE ±1.5% AT 200°C AND ±0.7% AT -55°C FROM T_A = +25 ±3°C.

3.3.1.4 DISSIPATION FACTOR. 0.15% MAXIMUM AT 25°C WHEN MEASURED AS SPECIFIED IN 4.3.3.

3.3.1.5 INSERTION LOSS. SHALL BE PERFORMED PER FIGURE 2 OF MIL-STD-220A, AT 400 HZ ± 10%.

3.3.1.6 PHYSICAL DIMENSIONS. AS REQUIRED.

3.3.2 DIELECTRIC WITHSTANDING VOLTAGE. WHEN TESTED AS SPECIFIED IN 4.2.4, CAPACITOR SHALL BE CAPABLE OF WITHSTANDING, POTENTIAL WITHOUT PERMANENT DAMAGE, OR OPEN/SHORT CIRCUITING.

3.3.3 INSULATION RESISTANCE. 695 MEGOHM MINIMUM BETWEEN TERMINAL AND CASE WHEN MEASURED AS SPECIFIED IN 4.2.5. FIGURE OF MERIT 125,000 MINIMUM (MEGOHMS X MICROFARADS = FIGURE OF MERIT) FOR THE 180 MFD AND A FIGURE OF MERIT OF 31,000 MINIMUM FOR THE 45 MFD CAPACITOR.

3.3.4 DC RESISTANCE. THE RESISTANCE FROM TERMINAL TO TERMINAL SHALL BE 0.3 MILLIOHM MAXIMUM.

3.3.5 TERMINAL CURRENT. ALL FEEDTHROUGH CONNECTIONS SHALL BE CAPABLE OF CARRYING 224 AMP CONTINUOUS, 435 AMPS FOR 5 SEC., AC, 400 HZ. THE NON-FEED THROUGH CONNECTIONS SHALL BE CAPABLE OF CARRYING 20.0 AMPS CONTINUOUS, AC, 400 HZ.

3.4 BURN-IN. WHEN TESTED AS SPECIFIED IN 4.2.15, CAPACITORS SHALL WITHSTAND THE EXPOSURE TO HIGH TEMPERATURE AND VOLTAGE WITHOUT DAMAGE.

3.5 ENVIRONMENTAL CHARACTERISTICS

3.5.1 TEMPERATURE RATING.

3.5.1.1 STORAGE TEMPERATURE. -65°C TO +200°C. (GOAL)

3.5.1.2 OPERATING TEMPERATURE. -55°C TO +200°C. (GOAL)

3.5.2 THERMAL SHOCK. CAPACITORS SHALL BE DESIGNED TO PASS THE TESTS AS SPECIFIED IN 4.2.6, CAPACITOR DESIGN SHALL BE ABLE TO WITHSTAND THE EXTREMES OF HIGH AND LOW TEMPERATURE WITHOUT DAMAGE.

3.5.3 MOISTURE RESISTANCE. CAPACITOR SHALL BE DESIGNED TO MEET THE TEST AS SPECIFIED IN 4.2.7, AND STILL MEET THE REQUIREMENTS OF 3.3.1.3, 3.3.1.4, 3.3.2 AND 3.3.3. ACTUAL MOISTURE RESISTANCE TESTS SHALL NOT BE PERFORMED.

3.5.4 SALT SPRAY (CORROSION). CAPACITORS SHALL BE DESIGNED TO MEET THE TEST AS SPECIFIED IN 4.2.8, THERE SHALL BE NO HARMFUL OR EXTENSIVE CORROSION, AND AT LEAST 90 PERCENT OF ANY EXPOSED METAL SURFACE OF THE CAPACITOR SHALL BE PROTECTED BY THE FINISH. HARMFUL CORROSION SHALL BE CONSTRUED AS BEING ANY TYPE OF CORROSION WHICH IN ANY WAY INTERFERES WITH MECHANICAL OR ELECTRICAL PERFORMANCE. IN ADDITION, THERE SHALL BE NO UNWRAPPING OF, OR MECHANICAL DAMAGE TO, THE INSULATING SLEEVES, WHEN APPLICABLE. ACTUAL SALT SPRAY (CORROSION) TESTS SHALL NOT BE PERFORMED.

3.5.5 FUNGUS. THE CONTRACTOR SHALL CERTIFY THAT ALL EXTERNAL MATERIALS ARE NON-NEUTRIENT. CAPACITORS SHALL BE DESIGNED TO MEET THE TEST AS SPECIFIED IN 4.2.9. ACTUAL FUNGUS TESTING SHALL NOT BE PERFORMED.

3.5.6 VIBRATION, HIGH FREQUENCY. CAPACITORS SHALL BE DESIGNED TO MEET THE TEST AS SPECIFIED IN 4.2.10, THERE SHALL BE NO EVIDENCE OF MECHANICAL DAMAGE, OR OPEN/SHORT-CIRCUITING UPON COMPLETION OF TEST. ACTUAL VIBRATION TESTING SHALL NOT BE PERFORMED.

3.5.7 SHOCK (SAWTOOTH PULSE). CAPACITORS SHALL BE DESIGNED TO MEET THE TEST AS SPECIFIED IN 4.2.11, THERE SHALL BE NO MECHANCIAL DAMAGE, NO EVIDENCE OF INTERMITTENT CONTACTS OF 0.5 MS OR GREATER DURATION, OR OPEN OR SHORT-CIRCUITING. ACTUAL SHOCK TESTING SHALL NOT BE PERFORMED.

3.6 SEAL. WHEN CAPACITORS ARE TESTED AS SPECIFIED IN 4.2.12, THERE SHALL BE NO REPETITIVE BUBBLING.

3.7 TERMINAL STRENGTH. WHEN TESTED AS SPECIFIED IN 4.2.13, THERE SHALL BE NO PERMANENT DAMAGE TO THE TERMINALS OR SEAL.

3.8 SOLDERABILITY. N/A

3.9 LIFE. CAPACITOR SHALL BE CAPABLE OF MEETING THE FOLLOWING REQUIREMENTS FOLLOWING A 1000 HOUR LIFE TEST WITH 120 VRMS, 400 HZ AT AN AMBIENT OPERATING TEMPERATURE OF 200°C.

C = ±10% FROM INITIAL MEASUREMENTS AT 25°C AMBIENT
DF = 0.35% MAXIMUM AT 1 KHZ AT 25°C AMBIENT
IR = 460 MEGOHM MINIMUM AT 25°C AMBIENT

3.10 FABRICATION CHANGES. THE CONTRACTOR SHALL NOT MAKE ANY CHANGES IN THE PRODUCT OR IN THE FABRICATION PROCESS WITHOUT PRIOR APPROVAL OF THE AIR FORCE.

3.11 MARKING. PART SHALL BE MARKED LEGIBLY AND PERMANENTLY PER MIL-STD-1285 WITH CONTRACTOR'S NAME, (OR SYMBOL), DATE CODE AND IDENT NUMBER, ON TOP OF CAPACITOR CASE.

3.11.1 SERIALIZATION. EACH CAPACITOR SHALL BE SERIALIZED.

3.12 DATA. DATA SHALL BE RECORDED FOR THE QUALITY CONFORMANCE TEST, GROUP A INSPECTION SPECIFIED IN PARAGRAPH 4.2.1.

3.13 MAXIMUM WEIGHT GOAL FOR THE 180 MFD CAPACITOR IS: 3.0 LB. FOR THE 45 MFD CAPACITOR, THE MAXIMUM WEIGHT GOAL IS: 0.5 LB.

3.14 ALL TERMINAL CURRENT CARRYING INTERFACES SHALL BE SOLDERED TO PROVIDE THE NORMAL CURRENT CONDUCTING PATH, SUCH THAT CURRENT IS NOT CARRIED THROUGH A THREADED INTERFACE.

4.0 QUALITY ASSURANCE PROVISIONS

4.1 RESPONSIBILITY FOR INSPECTION. THE CONTRACTOR IS RESPONSIBLE FOR THE PERFORMANCE OF ALL INSPECTION REQUIREMENTS AS SPECIFIED HEREIN. EXCEPT AS OTHERWISE SPECIFIED IN SECTION C OF THE PURCHASE REQUEST, THE CONTRACTOR MAY USE HIS OWN OR ANY OTHER FACILITIES SUITABLE FOR THE PERFORMANCE OF THE INSPECTION REQUIREMENTS SPECIFIED HEREIN, UNLESS DISAPPROVED BY THE AIR FORCE.

4.2 EXAMINATION AND TEST CRITERIA/SPECIFICATIONS

4.2.1 VISUAL AND MECHANICAL EXAMINATION. CAPACITOR SHALL BE EXAMINED TO VERIFY THAT THE MATERIALS, DESIGN, CONSTRUCTION, PHYSICAL DIMENSIONS, MARKING, AND WORKMANSHIP ARE IN ACCORDANCE WITH THE REQUIREMENTS SPECIFIED HEREIN.

4.2.2 CAPACITANCE (SEE 3.3.1.3). CAPACITANCE SHALL BE TESTED IN ACCORDANCE WITH METHOD 305 OF MIL-STD-202F. THE FOLLOWING DETAILS SHALL APPLY:

(A) TEST FREQUENCY - 1,000 ±100 HZ
(B) LIMIT OF ACCURACY - WITHIN ±1.0 PERCENT
(C) AC VOLTAGE - 1.0 VRMS

4.2.3 DISSIPATION FACTOR (SEE 3.3.1.4). DISSIPATION FACTOR SHALL BE MEASURED AT 1,000 ±5 HZ, 1.0 VRMS WITH A FOUR TERMINAL BRIDGE.

4.2.4 DIELECTRIC WITHSTANDING VOLTAGE (SEE 3.3.2). CAPACITOR SHALL BE TESTED IN ACCORDANCE WITH METHOD 301 OF MIL-STD-202F. THE FOLLOWING DETAILS AND EXCEPTION SHALL APPLY:

(A) TEST VOLTAGE - 168 VRMS, 60 HZ OR 400 HZ
(B) CONNECTIONS - BETWEEN EITHER TERMINAL AND CASE
(C) TEST VOLTAGE REGULATOR - +10% OR BETTER
(D) CURRENT RESISTOR - NOT APPLICABLE
(E) DURATION OF APPLICATION - 1 MINUTE MAXIMUM.

4.2.5 INSULATION RESISTANCE (SEE 3.3.3). CAPACITOR SHALL BE TESTED IN ACCORDANCE WITH METHOD 302 OF MIL-STD-202F. THE FOLLOWING DETAILS SHALL APPLY:

(A) TEST POTENTIAL - 200 VDC ±5%; 5 MIN. ±30 SECONDS.
(B) POINTS OF MEASUREMENT - BETWEEN EITHER TERMINAL AND THE CASE AT 25 ±3°C.

4.2.6 THERMAL SHOCK (SEE 3.5.2). CAPACITOR TEST SPECIFICATIONS SHALL BE IN ACCORDANCE WITH METHOD 107 OF MIL-STD-202F. THE FOLLOWING DETAILS AND EXCEPTIONS SHALL APPLY:

(A) TEST CONDITION LETTER - D
(B) MEASUREMENTS BEFORE AND AFTER CYCLING - PARAGRAPH 3.3.1.3, 3.3.1.4, AND 3.3.3.

(C) NUMBER OF CYCLES - 5
(D) HIGH TEMPERATURE - 200°C
(E) EXPOSURE TIMES AT EXTREMES - 1 HOUR

4.2.7 MOISTURE RESISTANCE (SEE 3.5.3). CAPACITOR TEST SPECIFICATIONS SHALL BE IN ACCORDANCE WITH METHOD 106 OF MIL-STD-202F. THE FOLLOWING DETAILS SHALL APPLY:

(A) INITIAL MEASUREMENTS - PARAGRAPH 3.3.3
(B) POLARIZATION VOLTAGE - 0 VOLTS
(C) LOADING VOLTAGE - NOT APPLICABLE
(D) FINAL MEASUREMENTS - PARAGRAPH 3.3.3

4.2.8 SALT SPRAY (CORROSION) (SEE 3.5.4). CAPACITOR TEST SPECIFICATIONS SHALL BE IN ACCORDANCE WITH METHOD 101 OF MIL-STD-202F. THE FOLLOWING DETAILS SHALL APPLY:

(A) TEST-CONDITION LETTER - B (48 HOURS)
(B) MEASUREMENTS AFTER EXPOSURE - NOT APPLICABLE

4.2.9 FUNGUS (SEE 3.5.5). CAPACITOR TEST SPECIFICATIONS SHALL BE IN ACCORDANCE WITH METHOD 508 OF MIL-STD-810.

4.2.10 VIBRATION, HIGH FREQUENCY (SEE 3.5.6). THE CAPACITOR TEST SPECIFICATIONS SHALL BE IN ACCORDANCE WITH MIL-STD-202F WHEN DETERMINING ITS ABILITY TO WITHSTAND THE VIBRATION ENVIRONMENT ENCOUNTERED IN NORMAL SERVICE. WHEN ACCOMPLISHED, THE TEST SHALL BE CONDUCTED AT AN ENDURANCE LEVEL, RANDOM VIBRATION SPECTRUM AT A FREQUENCY OF 50-2000 HZ. THE CAPACITOR SHALL BE SUBJECTED TO ELECTRICAL LOAD DURING THIS TEST. THE FOLLOWING DETAILS SHALL APPLY:

(A) MOUNTING - THE CAPACITOR SHALL BE MOUNTED AS REQUIRED.

(B) ELECTRICAL - THE CAPACITOR SHALL BE ELECTRICALLY ENERGIZED AT 115 VRMS, 60 HZ. THE OUTPUT WAVEFORM SHALL BE CONTINUOUSLY MONITORED. ANY DEVIATION OR DEGRADATION OF THE WAVEFORM FROM NORMAL SHALL BE CAUSE FOR INVESTIGATION AND REJECTION.

(C) VIBRATION SPECTRUM - THE VIBRATION INPUT SHALL BE RANDOM FOR FREQUENCIES FROM 50-2000 HZ. THE SPECTRUM SHALL BE IN ACCORDANCE WITH FIGURE 214-1 OF MIL-STD-202F.

(D) TEST TIME - THE TEST SHALL BE CONDUCTED FOR 2 HOURS IN EACH OF THREE MUTUALLY EXCLUSIVE PLANES.

(E) PASS-FAIL CRITERIA - IN ADDITION TO (B) ABOVE, THE CAPACITOR SHALL BE EXAMINED AFTER EACH PLANE OF VIBRATION FOR MECHANCIAL DAMAGE OR ELECTRICAL FAULTS. EVIDENCE OF SUCH DAMAGE OR FAULTS SHALL BE CAUSE OF REJECTION. THE FOLLOWING MEASUREMENTS SHALL BE MADE AT 25°C AMBIENT AFTER EACH PLANE OF VIBRATION AND THE CUMULATIVE DEVIATIONS SHALL NOT EXCEED THAT SHOWN.

MEASUREMENT	PARAGRAPH	CUMULATIVE DEVIATION
CAPACITANCE	3.3.1.3	±.10% FROM INITIAL MEASUREMENT
DISSIPATION FACTOR	3.3.1.4	0.35% MAXIMUM AT 1 KHZ
INSULATION RESISTANCE	3.3.3	460 MEGOHM MINIMUM
DC RESISTANCE	3.3.4	
SEAL	3.6	

4.2.11 SHOCK (SAWTOOTH PULSE) (SEE 3.5.7). CAPACITOR TEST SPECIFICATIONS SHALL BE IN ACCORDANCE WITH METHOD 213 OF MIL-STD-202F. THE FOLLOWING DETAILS SHALL APPLY:

(A) SPECIAL MOUNTING MEANS - RIGIDLY MOUNTED BY THE BODY WITH FOUR BOLTS ONLY.
(B) TEST-CONDITION LETTER - I.
(C) ELECTRICAL LOADING DURING SHOCK - NONE.
(D) MEASUREMENTS AFTER SHOCK. PARAGRAPH 3.3.1.3, 3.3.1.4 AND 3.3.3. FOLLOWED BY 3.5.3 FOLLOWED BY 3.3.1.3, 3.3.1.4 AND 3.3.3.

AFTER THE TEST, CAPACITORS SHALL BE VISUALLY EXAMINED FOR EVIDENCE OF FRACTURES, AND OHTER VISIBLE MECHANICAL DAMAGE.

4.2.12 SEAL (SEE 3.6). CAPACITORS SHALL BE TESTED IN ACCORDANCE WITH METHOD 112 OF MIL-STD-202F. THE FOLLOWING DETAILS SHALL APPLY:

(A) TEST-CONDITION A OR EQUIVALENT.
(B) MEASUREMENTS AFTER TEST - NOT APPLICABLE.

4.2.13 TERMINAL STRENGTH (SEE 3.7). CAPACITORS SHALL BE TESTED IN ACCORDANCE WITH METHOD 211 OF MIL-STD-202F. THE FOLLOWING DETAILS AND EXCEPTIONS SHALL APPLY:

(A) TEST CONDITION LETTER - E
(B) MEASUREMENTS AFTER TEST - NOT APPLICABLE.

FOLLOWING EACH IMMERSION, CAPACITORS SHALL BE BRUSHED WITH A COMMON HARDBRISTLE TOOTHBRUSH FOR 10 STROKES. BRUSHING FORCE SHALL BE 1 POUND.

4.2.14 SOLDERABILITY. N/A

4.2.15 BURN-IN (SEE 3.4). THE 180 MFD CAPACITORS SHALL BE EXPOSED TO 200°C +0°C, -5°C, 140 VRMS, 400 HZ FOR A PERIOD OF 96 HOURS MINIMUM OF WHICH 48 HOURS MINIMUM SHALL BE PERFORMED AFTER PART IS POTTED IN THE METAL CASE. THE 45 MFD CAPACITORS

SHALL BE EXPOSED TO 200°C +0°C, -5°C, 150 VRMS, 400 HZ FOR A PERIOD OF 96 HOURS MINIMUM OF WHICH 48 HOURS MINIMUM SHALL BE PERFORMED AFTER PART IS POTTED IN THE METAL CASE.

5.0 PREPARATION FOR DELIVERY. CAPACITORS SHALL BE PREPARED FOR DELIVERY IN ACCORDANCE WITH MIL-C-39028.

APPENDIX C

LIFE TEST DATA FOR METALLIZED POLYSULFONE AND ULTEM
FILM CAPACITORS AT 140 VRMS AND ELEVATED TEMPERATURES.
SAMPLE SIZE 10 EACH.

APPENDIX C. LIFE TEST DATA FOR METALLIZED POLYSULFONE AND ULTEM FILM CAPACITORS AT 140 Vrms AND ELEVATED TEMPERATURES. SAMPLE SIZE 10 EACH.

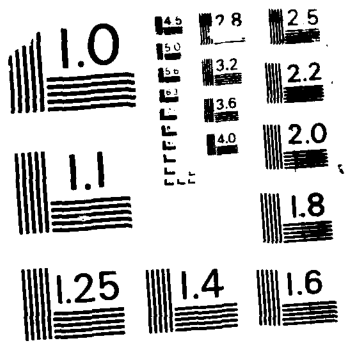
Temperature, ^{o}C	Hours to Failure	Total Hours	S/N	
			Polysulfone	Ultem
125	0.3	0.3	369	No failures
	24	24	368	
	168	168	358	
	744	744	350	
	2664	2664	356	
	3408	3408		
135	132	3540	No failures	No failures
140	0.1	3540.1	No failures	112
	88	3628		107, 111
145	28	3656	No failures	102
	120	3776		118
	184	3960		
150	48	4008	367	
	72	4080	351	
	96	4176		104, 109
	192	4368		
155	8	4376		105
	72	4448	370	
	144	4592		120
	192	4784	371	
	240	5024		113
	264	5288	359	

APPENDIX D

DU PONT SPECIFICATIONS FOR KAPTON POLYIMIDE FILM FOR USE AS A CAPACITOR DIELECTRIC

AD-A189 985 ADVANCED CAPACITOR DEVELOPMENT(U) HUGHES AIRCRAFT CO EL SEGUNDO CA R S BURITZ NOV 86 AFWAL-TR-86-2073 F33615-84-C-2424 2/2

UNCLASSIFIED F/G 9/1 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

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introduction

This specification provides information on the properties and characteristics of "Kapton"* polyimide film for use as a capacitor dielectric.

Specifications apply to film thickness of 30, 50, and 100 gauge, Type H film.

Tolerances are given for the various properties and characteristics. The maximum and/or minimum values represent a limiting condition which is approached by only a small percentage of the film.

Methods for measurement or test are described where necessary for thorough understanding.

physical property tolerances and test methods

TENSILE PROPERTIES(1)

GAUGE	TYPE	MINIMUM TENSILE STRENGTH psi(2)	MINIMUM ELONGATION %(2)
30	H	10,000	10
50	H	14,000	20
100	H	20,000	35

(1) Tensile strength and elongation tolerances apply to both machine and transverse direction.

(2) Minimum Average. An average of five specimens in either the machine or transverse direction is required to confirm that a slit roll meets our published tolerances

TENSILE STRENGTH (At Break)

Tolerances are based on tests run on an Instron Tensile Tester. This is a static weighing-constant rate of grip separation test such as described in ASTM D-882, Method A. (Specimen size 1" x 5"; separation between jaws 2"; elongation rate 2"/minute; chart speed 2"/minute.) Precise shear cut specimens are important. Edges must be paralleled within 2% of the width.

Tensile values are based on the original thickness of the specimens. Cross sectional area is obtained by measuring film thickness with a Comparator gauge (Ames) having a foot diameter of ¼". Thickness is measured to nearest .00001". Use an average of three measurements per specimen.

ELONGATION (At Break)

Obtained by Instron measurement as specified for tensile strength.

Reg U S Pat. Off.

DIMENSIONAL STABILITY (At 400°C)

The maximum shrinkage is:

100H 3%
50H 4%
30H 4%

Tolerance applies to both machine and transverse directions.

In order to confirm that the film meets our published tolerance, the following test should be run:

> Make three measurements in the machine direction and three in the transverse direction on each of a minimum of three specimens per slit roll at room temperature before and after test. Specimens (8½" x 11") should be freely suspended in an oven controlled to 400°C ±1°C for one-half hour.

electrical property tolerances and test methods (type h)[2]

DIELECTRIC STRENGTH (DC) (1)

CRITICAL TEST VOLTAGE	Number of Capacitors Which Must Survive Critical Test Voltage per 20 Capacitors (3)			Test Method
	30H	50H	100H	0.5 mfd. unimpregnated single-layer capacitors are subjected to D.C. voltage at 100 volts/second rate of rise at room temperature and 50% R.H. Tests to be conducted on as-wound units using 2" wide film and a ⅛" arbor. Units failing a 6-volt shorting test shall be discarded.
300	19			
500	16	19		
700		16		
1500			19	
Minimum Average Voltage of 20 Capacitors	900	1200	1800	

(1), (2) and (3) See Page 4 for references

INSULATION RESISTANCE (200°C) (Megohm-microfarads)

GAUGE AND TYPE	MINIMUM (4) AVERAGE	Test Method
30H	45	Measured on 0.5 mfd. unimpregnated, single-layer capacitors. 3 min. total electrification (2 min. charge, 1 min. operation at 100 volts D.C., using General Radio megohm bridge model 544-BS4 or equivalent). Preheat capacitors in oven at 200°C ±1°C for one-half hr. prior to test. Maintain temperature at 200°C ±1°C during measurement of capacitor resistance and capacitance.
50H	30	
100H	15	

DISSIPATION FACTOR (25°C) (Maximum at 1 KHz)

GAUGE AND TYPE		Test Method
30H	.007	Test according to ASTM D-150 using conducting silver paint electrodes two terminal system of measurement. Condition sample to 50% R.H. for 24 hrs. and test at 25°C. Results are based on an average of 5 tests using actual thickness of sample.
50H	.005	
100H	.004	

DIELECTRIC CONSTANT (25°C) (1)

Measured at 1 KHz using same test method as for dissipation factor:

	30H—50H—100H
Minimum	2.8
Maximum	4.0

REFERENCES

(1) Samples conditioned at room temperature and 50% R.H. for 24 hrs

(2) Applicable to samples from the same mill roll lot.

(3) This number has been statistically determined. Normally, it will be met by any group of 20 capacitors. However, to definitely prove, statistically, that the specified number has been met for any mill roll lot of materials, it will be necessary to wind 60 capacitors from 3 slit rolls (20 from rolls A and B, 20 from B and C, and 20 from A and C). If the average of the 3 groups is lower than the allowable number, the material is rejectable.

(4) Minimum average of 5 units

manufacture

MATERIAL

A polyimide polymer in the form of a film.

UNIFORMITY

Material shall be uniform in composition and as free from defects which impair functionality and/or appearance of the consumer product as process capabilities permit.

CORES

Plastic cores with 3.032" ±.012" inside diameter shall be used when film width is from minimum width up to 4". Film wider than 4" shall be wound on fibrous cores of 3" I.D. All 1⅛" cores are plastic.

PUT-UPS

Slit rolls are available as follows:

GAUGE	PUT-UP*	NOMINAL LENGTH
30H**	3" I.D. x 4⅞" O.D.	3,000 ft.
50H	3" I.D. x 6" O.D.	3,000 ft.
	1⅛" I.D. x 4" O.D.	1,600 ft.
100H	3" I.D. x 6" O.D.	1,500 ft.
	1⅛" I.D. x 4" O.D.	800 ft.

*O.D. Tolerance is ± ¼"

**30H also available on 1⅛" cores subject to prior approvals.

Cores shall be flush with roll face or core width shall be within ±1/32" of nominal film width. Core edges shall not project more than 1/32" beyond face of roll on either side.

The outside and starting ends of the film shall be fastened in such a manner as to prevent unwinding.

Film shall not project more than 1/16" from a straight edge laid flat across the diameter of the roll.

Tolerance for "shiners"* of 1/32" to 1/16" extension are as follows:

GAUGE	Number of "Shiners" Permitted per Roll End
100H	3
50H	6
30H	9

*A single or multiple layer of film extending beyond the edge of a slit roll which, if folded over, displays a "shiny" appearance.

SPLICES

The splices on 30H, 50H, and 100H "Kapton" polyimide film are of a butt type with 1" wide colored pressure-sensitive tape on each side.

Maximum splices permitted in each standard length roll are

100H	2
50H	5
30H	9

Minimum distance between splices or from beginning or end of slit roll is 100 ft. for 100H and 50H film, and 70 ft. for 30H film. However, the minimum average splice-free lengths are 500 ft. for 100H and 50H, and 300 ft. for 30H.

SLIT WIDTH TOLERANCES (30H, 50H, and 100H)

WIDTH	SLITTING TOLERANCE
1" and under	±1/64"
1 1/16" to 4" (inc.)	±1/32"
Over 4"	±1/16"

THICKNESS

Average thickness variations per single slit roll are as follows:

GAUGE	MINIMUM	MAXIMUM
100H	.88 mils	1.12 mils
50H	.40 mils	.62 mils
30H	.25 mils	.35 mils

Thickness measured in accordance with ASTM D-374, Method A or C.

Values are the average of ten randomly located readings from a minimum area of 12 sq. inches.

packaging and marking

A. PACKAGING

Material shall be adequately packed to prevent loss of contents or damage during shipment.

All film will be wrapped with a non-fibrous material (poly bags).

B. MARKING

Material is identified as follows:

	SHIPPING CONTAINER	PACKAGE	CORE LABEL (a)
Scheduled Date	X	X	X
Customer Order No.	X	X	
Du Pont Order No.	X	X	X
Gauge	X	X	X
Type	X	X	X
Width	X	X	X
No. of Rolls per Container	X	X	
Net Weight	X	X	
Footage			X
Mill Roll No.			X
I.D. & O.D. (b)	X	X	

(a) Affixed to the core on all 3" I.D. cores. 2" wide and over Included with the package on all 3" I.D. cores less than 2" wide.

(b) Inside diameter of core and nominal outside diameter of roll

ASSURANCE

Statistically confirmed sampling techniques both as to sample size and frequency shall be employed at our plants to insure that the average values of the previously described properties and characteristics are maintained within their respective limits. In the event of question, representative records of the various quality control tests are available for inspection.

APPENDIX E

CAPACITOR DESIGN CALCULATIONS

NUMBER OF PLATES

To find the number of plates, calculate the capacitance from the formula for a parallel plate capacitor:

$$C = 0.225 \frac{Ak}{t} \cdot 10^{-6} \ \mu F \qquad \text{(E-1)}$$

where

A = area = 3 in. • 4.7 in. = 14.1 in.^{2}

k = dielectric constant for Kapton at 25°C = 3.5

t = thickness = 0.0003 in.

then the capacitance is

$$C = 0.225 \frac{14.1 \cdot 3.5}{0.0003} \cdot 10^{-6}$$

$$= 0.037102 \ \mu F \text{ per plate}$$

Then the number of plates for 180 μF is

$$N = 180/0.037012 = 4863$$

CONDUCTOR POWER LOSS

Calculate the resistance of the aluminum conductor or load current bus as follows:

$$\text{Cross Section} = 3\ \text{in.} \cdot 0.0002\ \text{in.} \cdot 2431 = 1.4586\ \text{in.}^2$$

Assume bus length of five inches, then resistance is

$$R = 2.65 \cdot 10^{-6}\ \Omega$$

Power loss in conductor is

$$P = I^2R\ (225)^2 \cdot 2.65 \cdot 10^{-6} = 0.134\ \text{watts}$$

TOTAL RESISTANCE

Assume a resistance of $40 \cdot 10^{-6}$ ohms for the lugs and the connection of the lugs to the aluminum. From above, the resistance of the aluminum conductor is $2.65 \cdot 10^{-6}$ ohms. The total resistance then is $42.65 \cdot 10^{-6}$ ohms. This value is substantially less than the $300 \cdot 10^{-6}$ ohms maximum specified in the requirements.

DIELECTRIC HEATING

The power loss in the dielectric can be calculated using the following formula:

$$P = k \cdot DF \cdot E^2 \cdot f \cdot V \cdot 5.556 \cdot 10^{13}\ \text{watts}$$

where

P = power loss in watts

k = dielectric constant = 3.5

DF = dissipation factor = 0.0025

E = voltage gradient, V/cm = 19680 for 150V

f = frequency = 400 Hz

V = insulation volume = 333 cm^3

Then,

P = 25.09 watts loss in dielectric heating

APPENDIX F

CAPACITOR TEST PLAN

Report No. FR 86-76-583
HAC Ref No. F7154

ADVANCED CAPACITOR DEVELOPMENT
Contract F33615-84-C-2424

TEST PLAN

March 1986

Prepared for:

Aero Propulsion Laboratory
Air Force Wright Aeronautical Laboratories
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

Technology Support Division
ELECTRO-OPTICAL AND DATA SYSTEMS GROUP
Hughes Aircraft Company
El Segundo, California 90245

CONTENTS

1.0 INTRODUCTION

This document contains the Test Plan required for Contract F33615-84-C-2424 by DD Form 1423, sequence number 5. This report conforms to the requirements of DD 1423, and in addition to the requirements contained in paragraph 4.2 of section C- Description/Specifications and Addendum # 1 to section C, Detailed Specification.

2.0 PURPOSE AND OBJECTIVES

Paragraph 4.2 of the Description/Specification contains a requirement that performance tests be performed for both types of capacitors, incorporating applicable electrical performance tests as specified by Addendum # 1 to the Description/Specification.

These tests will establish the capacitor electrical characteristics. In addition, performance capabilities will be determined under limited environmental conditions. Burn-in tests and life tests at 200°C will demonstrate that the design is good for high temperature operation. To these, other tests have been added by the Contractor, who believes that they will further assist in proving the design.

Moisture resistance, salt spray, fungus, vibration and mechanical shock will not be performed as required by respective sub-paragraphs of 3.5.

3.0 ASSEMBLIES TO BE TESTED

Two different types of assemblies will be tested to provide better quality control and reliability. Capacitor pads will be inspected during manufacture followed by acceptance tests of the complete encased capacitor assembly.

3.1 COMPLETE CAPACITOR ASSEMBLIES

Completely assembled capacitors will be used in the majority of the testing. These capacitors will be made using the designs developed as per paragraph 4.1 of the Description/Specifications. These designs (Dwg. No. 864053 and 864054) also have been reviewed per paragraph 4.1.3 of the Description/ Specifications.

3.2 CAPACITOR PAD ASSEMBLIES

Certain of the tests, for example, capacitance and dissipation factor will be performed first on the capacitor pad assembly before assembling the case to insure the parts have been assembled properly and are electrically satisfactory. A pad assembly is the compressed stack of dielectric and conducting film with the base plate.

4.0 TESTS AND TEST SET-UPS

The following tests will be carried out as performance tests of the AC filter capacitors:

- o Visual and Mechanical Examination
- o Capacitance
- o Dissipation Factor
- o Dielectric Withstanding Voltage
- o Insulation Resistance
- o Thermal Shock
- o Seal
- o Terminal Strength
- o Burn-in
- o Life

In the sections that follow, each test is described, the actual test set-ups are described, the required equipment is identified, test procedures and parameters are given.

All measurements will be performed with equipment and instruments that are maintained and calibrated by the Hughes Standards Laboratory which is referenced to the National Bureau of Standards. Data will be recorded in a log book or data sheet by serial number, with the date, equipment and instruments used, and signed by those persons conducting the tests.

4.1 VISUAL AND MECHANICAL EXAMINATION

Careful visual examination will insure that all parts and assemblies are of good workmanship, free of visible defects, and are in accordance with the drawings/specifications.

Mechanical examination will insure that all parts and assemblies are dimensionally correct, within the specified tolerances, and in accordance with the drawings/specifications.

4.1.1 Incoming Quality Control

A visual and mechanical inspection per Dwg No. 864053 and 864054 will be performed on all parts when they are received as part of the normal incoming quality assurance.

4.1.2 In-Process Quality Control

In-process inspection will consist of visual and mechanical examination of each capacitor during assembly to ensure conformity with Dwg No. 864053 and 864054. Particularly, the solder joint between the terminal and the terminal end plate will be inspected to see that the joint is wetted and properly positioned. The capacitor pad assembly will be inspected after stacking and again after the termination's are made. Finally, the capacitor will be inspected after the case is welded.

4.2 CAPACITANCE

The purpose of this test is to measure the capacitance (C) of components parts and the capacitance of the complete capacitor assembly.

4.2.1 Test Conditions

Tests will be conducted per MIL-STD-202F, method 305, except the following details shall apply:

1) Test frequency - 1,000 $\pm$ 100 Hz
2) Limit of accuracy - within $\pm$ 1%
3) AC voltage - 1.0 Vrms

4.2.2 Test Equipment

The measurements will be made with an HP 4262A Digital LCR Meter.

4.2.3 Test Sequence

The test sequence is :

1) Measure capacitance of pad assembly at ambient temperature.
2) As required by paragraph 4.10.2, Burn-In.
3) As required by paragraph 4.11.2, Life Test.
4) As required by paragraph 4.8, Thermal Shock.

4.3 DISSIPATION FACTOR

The purpose of this test is to measure the dissipation factor (D.F.) of the capacitor pad and terminations, and the dissipation factor of the complete capacitor assembly. The dissipation factor is a measure of losses in a capacitor, i.e., the fraction of the input volt-amperes that is dissipated in the capacitor.

4.3.1 Test Conditions

Dissipation factor will be measured at 1,000 $\pm$ 5Hz with 1.0Vrms.

4.3.2 Test Equipment

The measurements will be performed with an HP 4262A Digital LCR Meter using the four-terminal arrangement.

4.3.3 Test Sequence

Measurements of the dissipation factor will be made after each capacitance measurement. Hence, the test sequence is the same as that for capacitance, see paragraph 4.2.3.

4.4 INSULATION RESISTANCE

This test is to measure the resistance offered by the insulating members of a component to an impressed direct voltage tending to produce a leakage current through or on the surface of these members. Insulation resistance (I.R.) measurements are important as these values may be limiting factors in the circuit design.

4.4.1 Test Conditions

Tests will be conducted per MIL-STD-202F, method 302, except the following details shall apply:

1) Test potential - 200 VDC ± 5%
2) Electrification time - 5 minutes ± 30 seconds
3) Points of measurement - between either terminal and the case at 25° ± 3°C.

4.4.2 Test Equipment

The measurements will be made with a Beckman Megohmmeter, Model L-8.

4.5 DIELECTRIC WITHSTANDING VOLTAGE

This test consists of the application of a voltage higher than rated voltage for a specific time between mutually insulated portions of a component part or between insulated portions and ground. This test is used to prove that the component part can operate safely at its rated voltage and withstand momentary over-potentials. It is not intended that this test cause insulation breakdown, rather it serves to determine whether insulating materials and spacing in the component part are adequate. When a component is faulty, application of the test voltage will result in either breakdown or deterioration.

4.5.1 Test Conditions

Tests will be conducted per MIL-STD- 202F, method 301. The following details and exceptions shall apply:

1) Test voltage - 168 Vrms, 60 Hz (or 400 Hz).

2) Voltage measuring device - A voltmeter shall be used to measure the applied voltage to an accuracy of at least 5 percent.

3) Connections - Between either terminal and case.

4) Test voltage regulator - $\pm$ 10 % or better.

5) Rate of application - approximately 500 Vrms per second.

6) Duration of application - 1 minute maximum.

4.5.2 Test Equipment

Power source and circuitry to provide turn-on and rate of application.

4.6 INSERTION LOSS

This test measures the loss obtained when the capacitor is connected into a transmission system. The loss is represented as the ratio of input voltage required to obtain constant output, in the specified 50 ohm system.

4.6.1 Test Conditions

Tests will be conducted per MIL-STD-202A per Figure 2 at 400 Hz $\pm$ 10%.

4.7 TERMINAL STRENGTH

This test is performed to determine whether the design of the terminals and their method of attachment can withstand one or more of the mechanical stresses to which they will be subjected during installation. The torque exerted will disclose poor workmanship, faulty designs, and inadequate methods of attaching terminals to the body of the part.

4.7.1 Test Conditions

Tests will be conducted per MIL-STD-202F, method 211A. The following details shall apply:

1) Test condition E - Torque test.

2) Torque - 40 ounce - inches for 9/32 inch equivalent diameter.

4.8 THERMAL SHOCK

This test is conducted to determine the resistance of a component to exposures at extremes of high and low temperatures and to the shock of alternate exposures to these extremes. Permanent changes in operating characteristics and physical damage produced during thermal shock result principally from variations in dimensions and other physical properties.

4.8.1 Test Conditions

Test will be conducted per MIL-STD-202F, Method 107G. The following details and exceptions apply:

1) Test Condition letter - D
2) Number of cycles - 5
3) Temperature extremes - +200°C and -65°C
4) Exposure at extremes - 1 hour

5) Measurements - capacitance, dissipation factor, and insulation resistance shall be measured before and after cycling at ambient temperature.

4.8.2 Test Equipment

The capacitance and dissipation factor measurements will be made with an HP 4262A Digital LCR Meter. The insulation resistance measurements will be made with a Beckman Megohmmeter.

4.9 SEAL

The purpose of this test is to determine the effectiveness of the seal of a component which has an internal cavity which is either evacuated or contains air or gas. The specified test condition is a bubble test in heated oil. The nominal sensitivity is about 10^{-5} atm cm^3/sec.

4.9.1 Test Conditions

Tests will be conducted per MIL-STD-202F, Method 112D, except the following details apply:

1) Test Condition - Bubble test using mineral oil or peanut oil at 125° $\pm$3°C.
   Nominal sensitivity is about 10^{-5} atm cm^3/sec.

4.10 BURN-IN

Capacitors will be burned-in at high temperature and voltage. This test is used to prove that a component part can operate reliably at over-potential and high temperature extreme. It is used prior to life test as a screening test to eliminate infant mortality failures. The voltage will be supplied directly from a 250 kW 400 Hz motor-generator.

4.10.1 Test Conditions

Capacitor assemblies will be burned-in prior to conducting the life test. The following details apply:

1) Temperature - 200°C + 0°C, - 5°C
2) Duration of Test - 96 hours minimum
3) Voltage - 140 Vrms 400 Hz for 180 uF capacitor
   - 150 Vrms 400 Hz for 45 uF Capacitor

4.10.2 Test Sequence

The test sequence is:

1) Measure capacitance before and after burn-in at ambient temperature.

2) Measure dissipation factor before and after burn-in at ambient temperature.

3) Measure insulation resistance before and after burn-in at ambient temperature.

4.11 LIFE TEST

Life tests will be conducted to demonstrate the applicability of the developed capacitors to the particular engineering problem posed by service at 200°C ambient. The voltage will be supplied from a 250 kW 400 Hz motor-generator. Only complete capacitor assemblies will be tested.

4.11.1 Test Conditions

Life tests will be conducted after the burn-in test. The following details apply:

1) Temperature - 200°C

2) Duration - 1,000 hours

3) Voltage - 120 Vrms, 400 Hz

4.11.2 Test Sequence

The test sequence is:

1) Measure the capacitance before and after the life test.

2) Measure the dissipation factor before and after the life test.

3) Measure the insulation resistance before and after the life test.

4) If a capacitor failure occurs, the failed capacitor will be replaced up to the limit of assembled units.

5.0 OVERALL TEST PLAN

It is anticipated that some tests will be run in sequence, some in series. This section gives the general plan.

5.1 ARRANGEMENT OF TESTS

The tests will be conducted in the following time phase:

Capacitor Pad Assemblies

I: Visual and Mechanical
C, D.F., I.R.
Dielectric Withstanding Voltage
Insertion Loss

(C, D.F., I.R.; Dielectric Withstanding Voltage; Insertion Loss) Simultaneously

Capacitor Assemblies

II: Visual and Mechanical
C, D.F.
Terminal Strength

(Visual and Mechanical; C, D.F.) Simultaneously

III: Thermal Shock

IV: Burn-in

V: Life

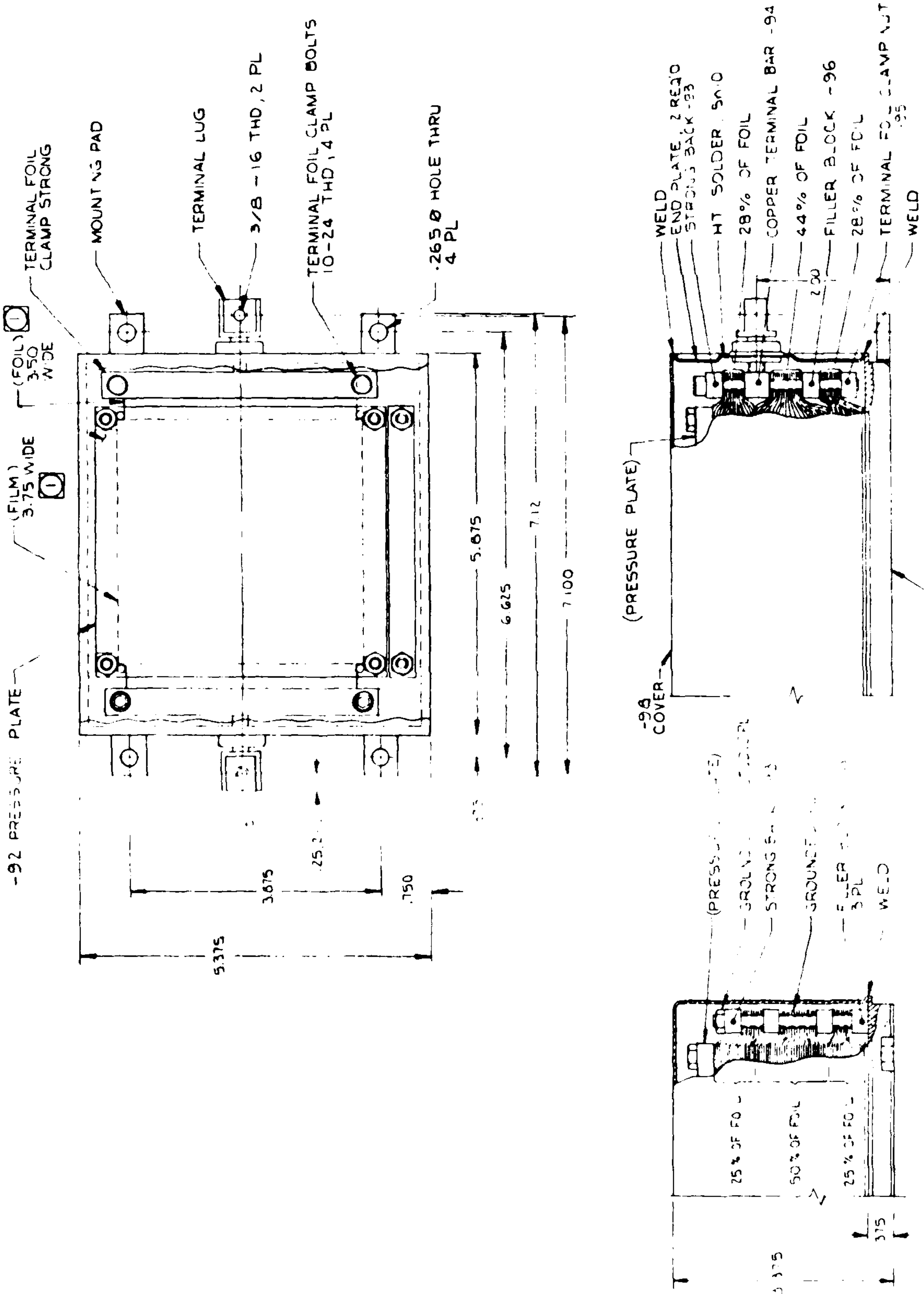
VI: C, D.F.

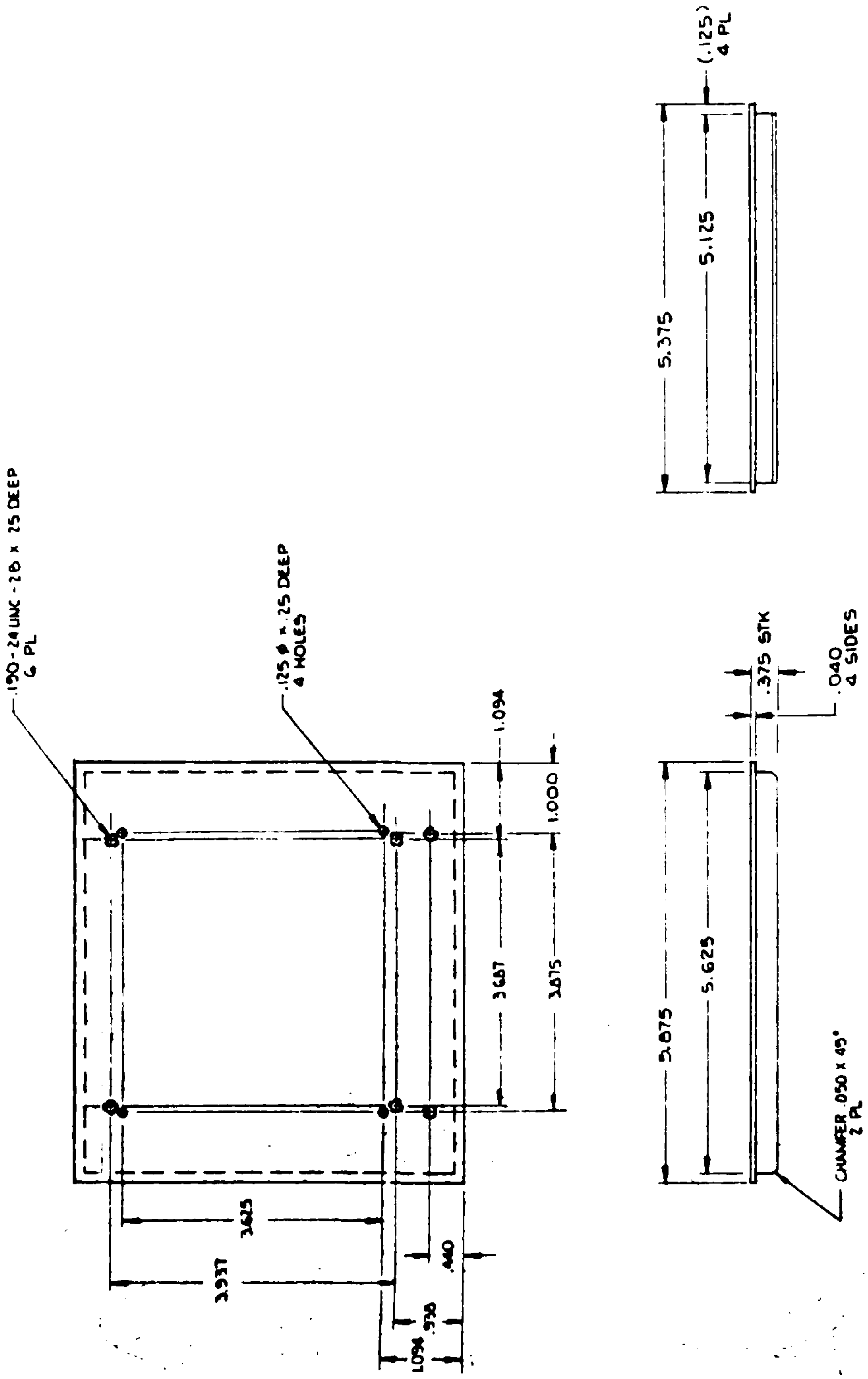
6.0 UNUSUAL TESTS

None of these tests is particularly unusual. All tests do not have equal weight, the life test being more significant than dielectric withstanding voltage, for example.

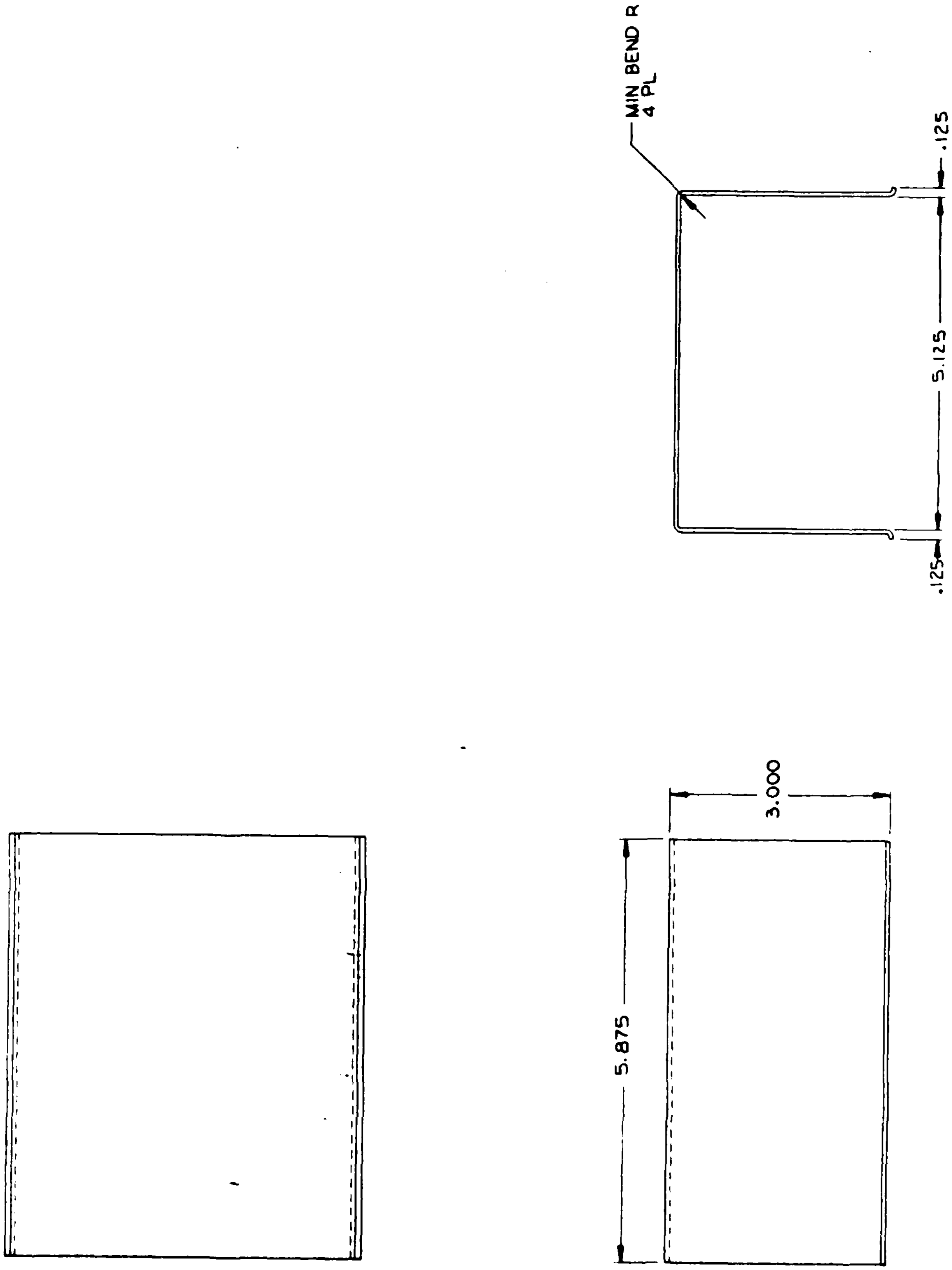
APPENDIX G

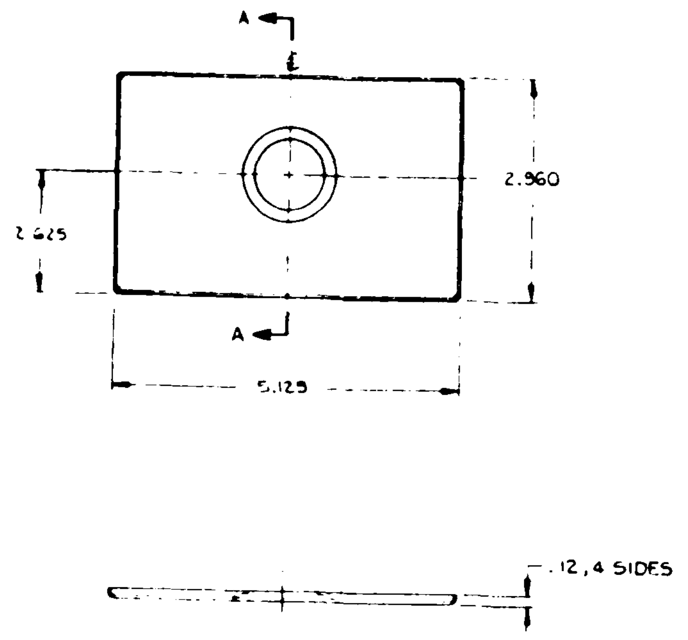
CAPACITOR, AC FILTER - 45 μF

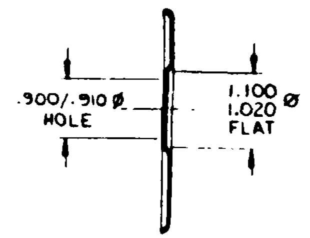

TERMINAL FOIL CLAMP STRONG
TERMINAL LUG
3/8 -16 THD, 2 PL
TERMINAL FOIL CLAMP BOLTS 10-24 THD, 4 PL
.265 Ø HOLE THRU 4 PL
(FOIL) 3.50 WIDE
(FILM) 3.75 WIDE
PLATE
5.875
6.625
7.12
7.100
3.875
.750
5.375
WELD
HT SOLDER
28% OF FOIL
COPPER TERMINAL BAR -94
44% OF FOIL
FILLER BLOCK -96
WELD
(PRESSURE PLATE)
-98 COVER
BASE
25% OF FOIL
50% OF FOIL



.190-24 UNC-2B x .25 DEEP 6 PL
.125 ϕ x .25 DEEP 4 HOLES
1.094
1.000
3.687
3.875
3.625
3.937
.440
.938
1.094
(.125) 4 PL
5.375
5.125
.375 STK
.040 4 SIDES
5.875
5.625
CHAMFER .050 x 45° 2 PL


MIN BEND R
4 PL
.125
5.125
.125
3.000
5.875



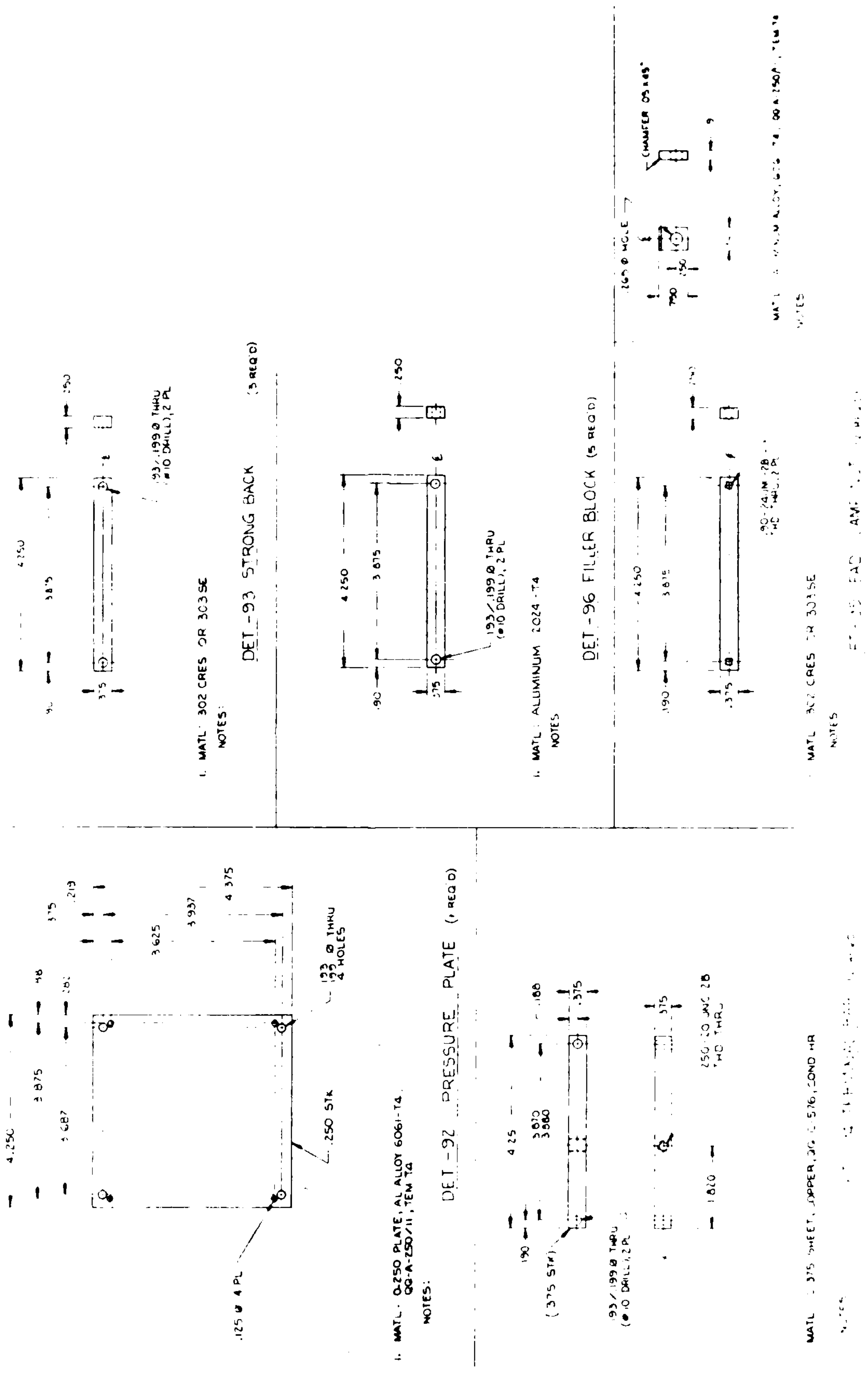


SECTION A-A
(THROUGH TERMINAL
END PLATE)

NOTES:

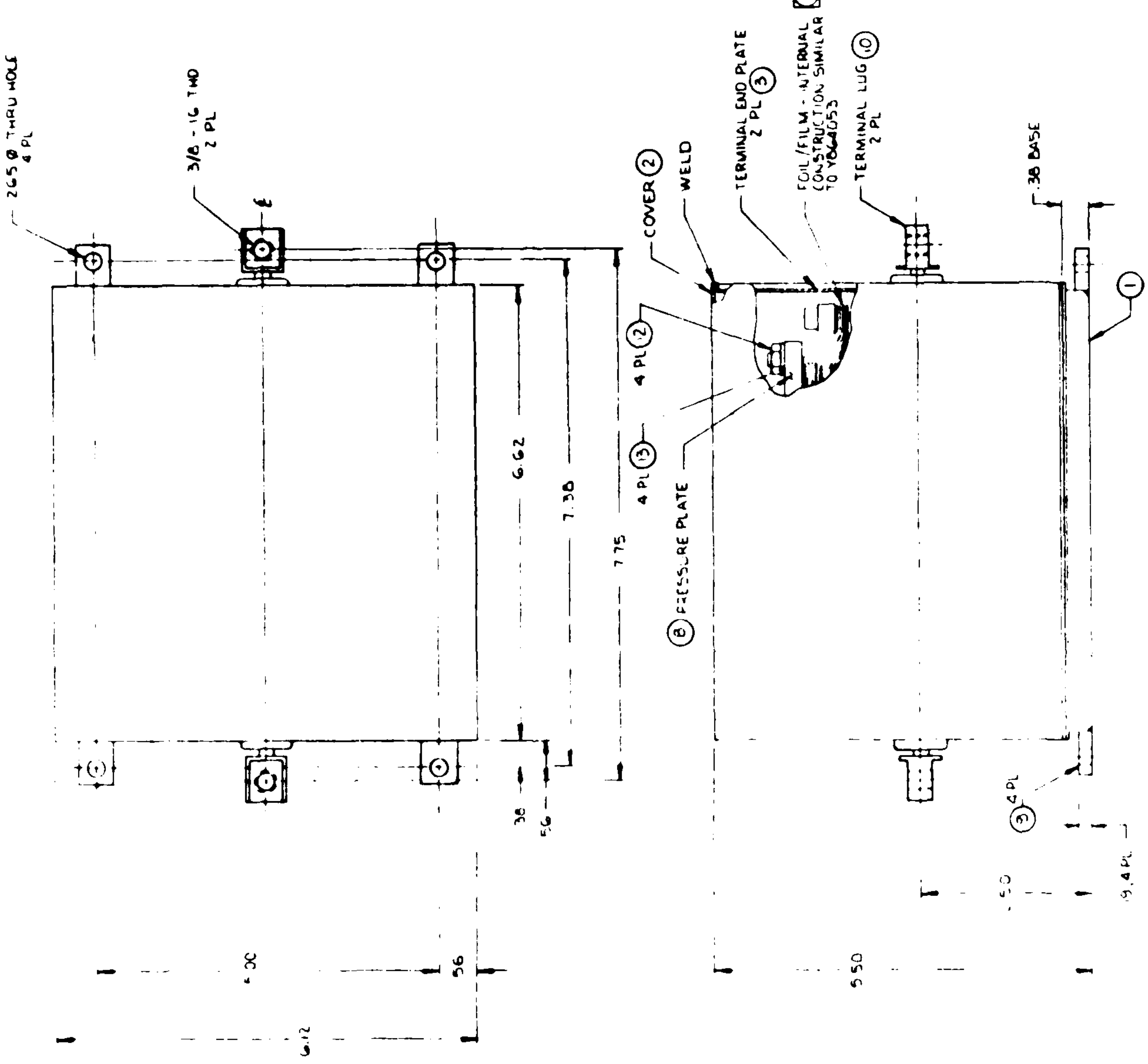
1. MATL: 0.040 SHEET, AL ALLOY 6061-T4, QQ-A-250/11, TEM T4

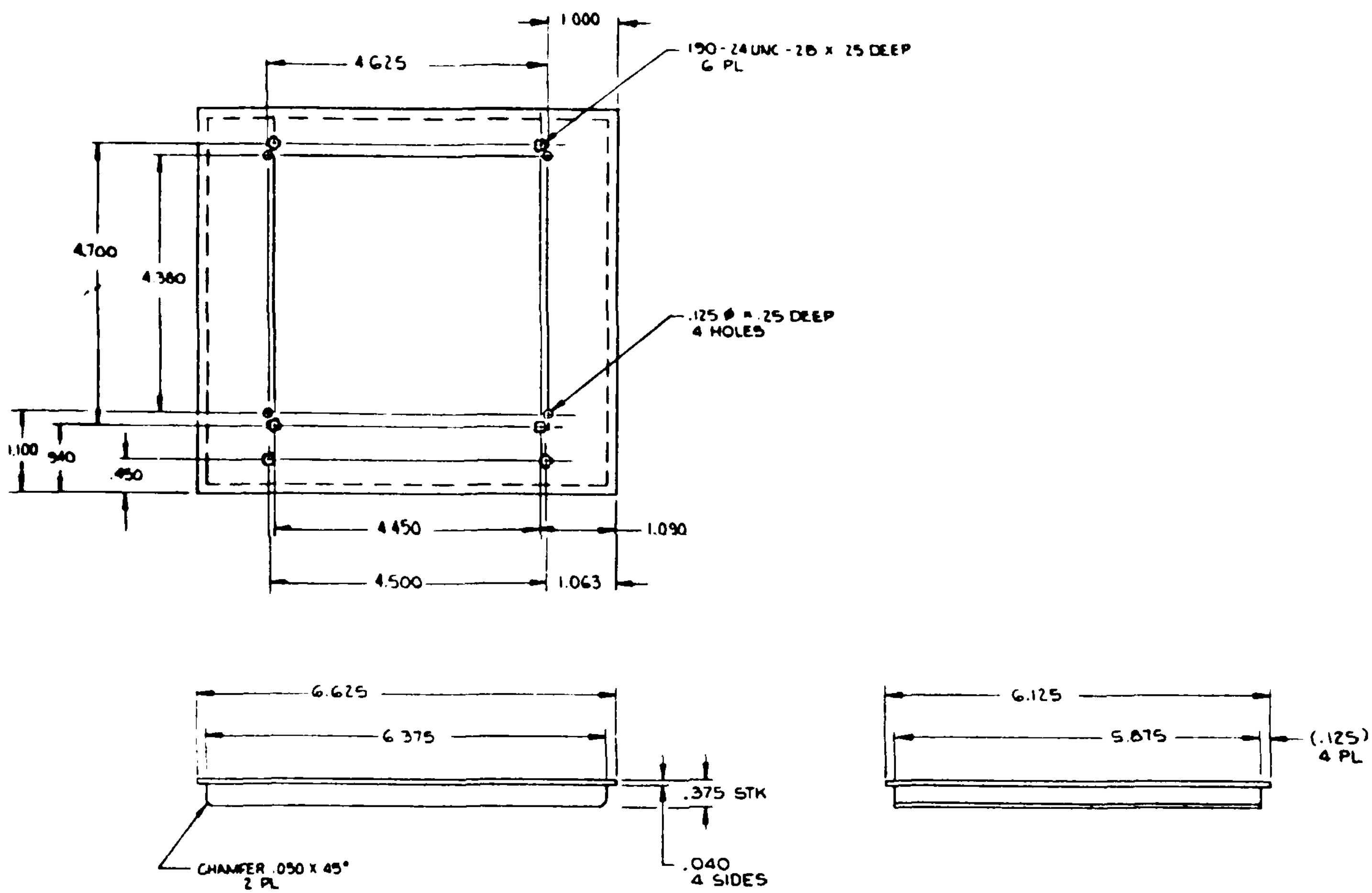
DET -97 TERMINAL END PLATE (2 REQ'D)


DET-93 STRONG BACK (5 REQ'D)
NOTES:
1. MATL: 302 CRES OR 303 SE
.193/.199 Ø THRU (#10 DRILL), 2 PL
DET-96 FILLER BLOCK (5 REQ'D)
NOTES:
1. MATL: ALUMINUM 2024-T4
DET-92 PRESSURE PLATE (1 REQ'D)
NOTES:
1. MATL: 0.250 PLATE, AL ALLOY 6061-T4, QQ-A-250/11, TEM T4
.125 Ø 4 PL
.250 STK
4 HOLES

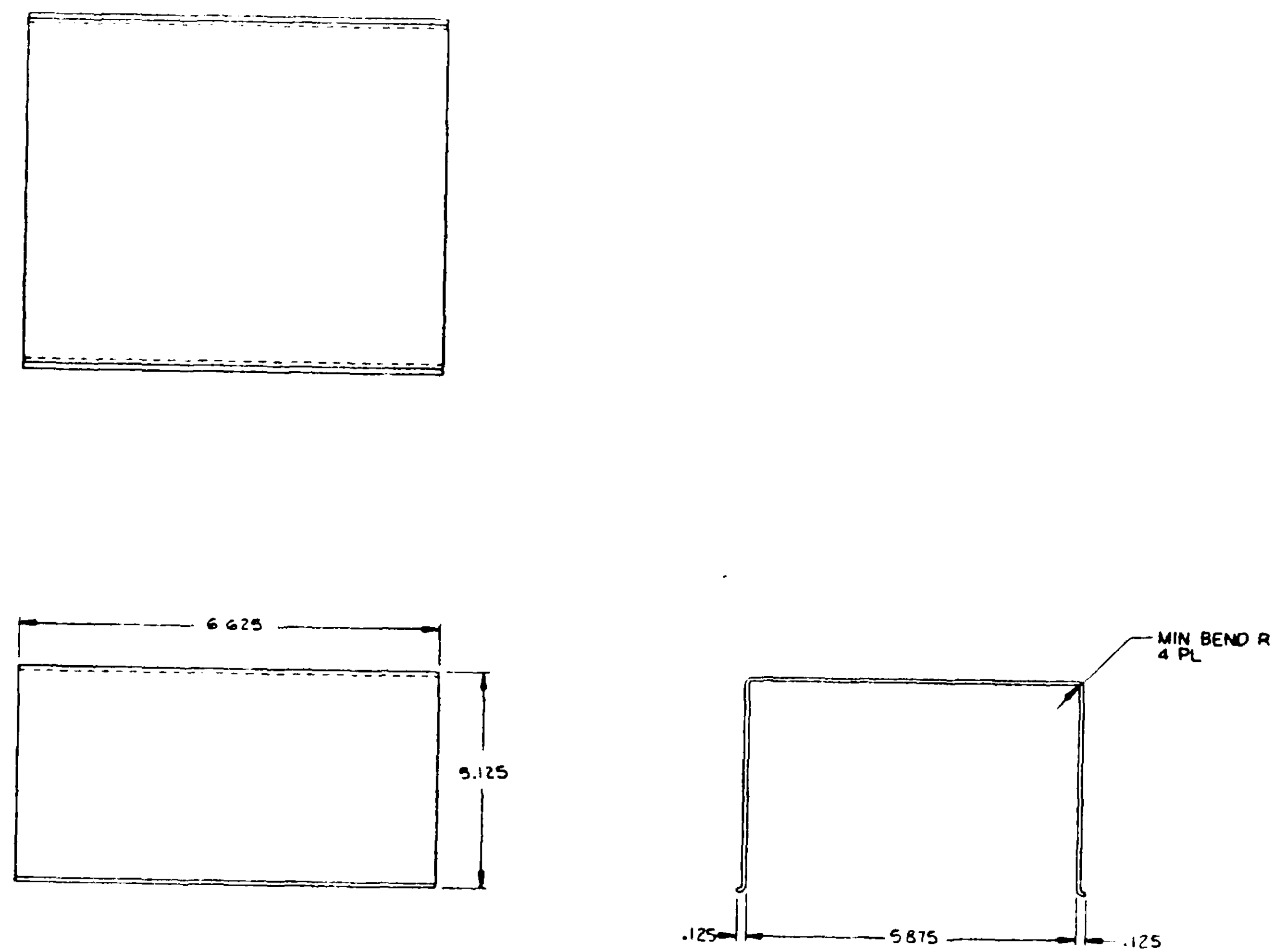
APPENDIX H

CAPACITOR AC FILTER - 180 μF

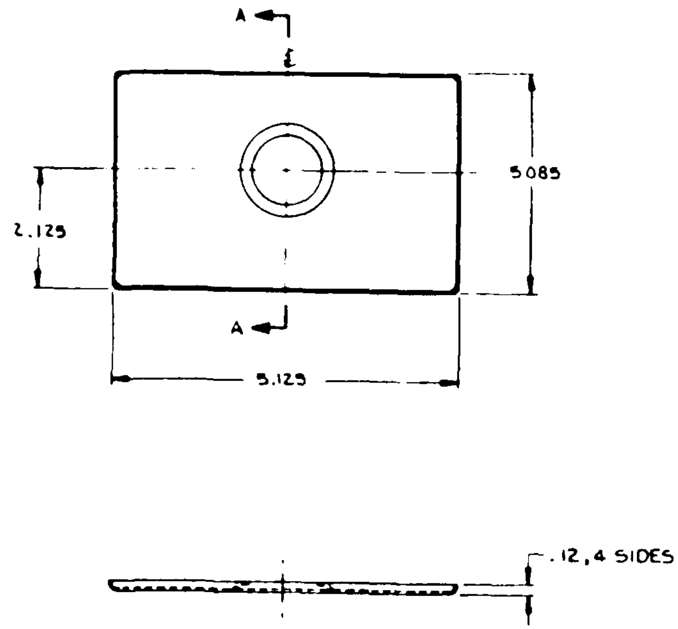

.265 Ø THRU HOLE 4 PL
3/8 - 16 THD 2 PL
COVER (2)
WELD
TERMINAL END PLATE 2 PL (3)
FOIL/FILM - INTERNAL CONSTRUCTION SIMILAR TO Y044053
TERMINAL LUG (10) 2 PL
.38 BASE
4 PL (2)
4 PL (13)
(8) PRESSURE PLATE
6.62
7.38
7.75
.38
.56
.56
6.12
5.50
(9) 4 PL

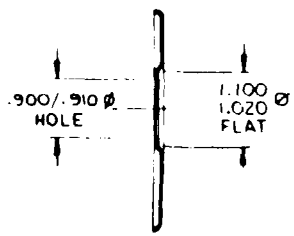


DET -99 BASE (1 REQ'D)



DET -98 COVER (1 REQ'D)



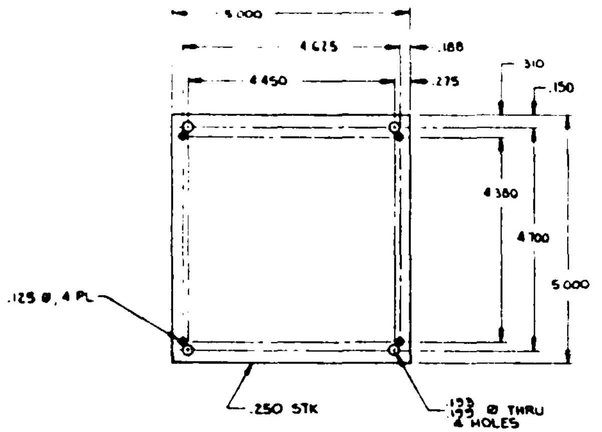


SECTION A-A
(THROUGH TERMINAL
END PLATE)

1. MATL: 0.040 SHEET, AL ALLOY 6061-T4, QQ-A-250/11, TEM T4

NOTES:

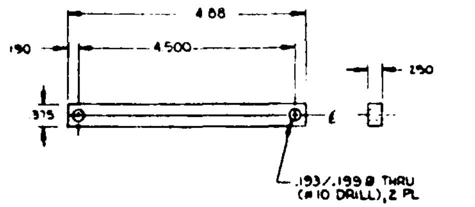
DET-97 TERMINAL END PLATE (2 REQ'D)



1. MATL: 0.250 PLATE, AL ALLOY 6061-T4, QQ-A-250/11, TEM T4

NOTES:

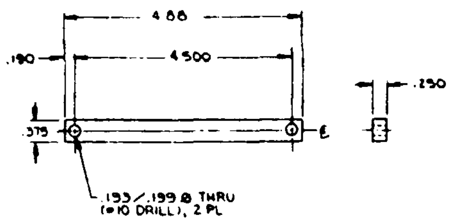
DET -92 PRESSURE PLATE (1 REQ'D)



1. MATL: 302 CRES OR 303 SE

NOTES:

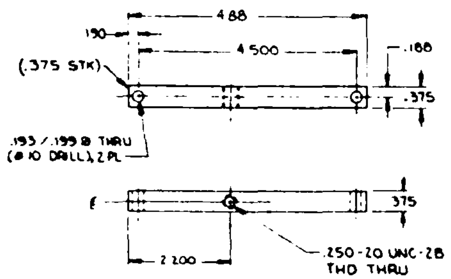
DET -93 STRONG BACK (3 REQ'D)



1. MATL: ALUMINUM 2024-T4

NOTES:

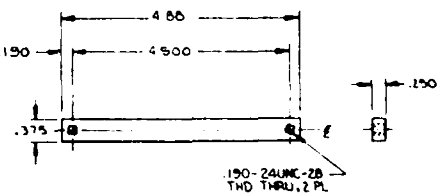
DET -96 FILLER BLOCK (18 REQ'D)



1. MATL: 0.375 SHEET, COPPER, QQ-C-576, COND HA

NOTES:

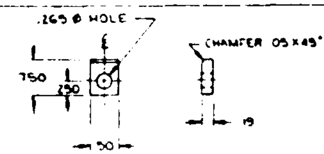
DET -94 TERMINAL BAR (2 REQ'D)



1. MATL 302 CRES OR 303 SE

NOTES

DET -95 LEAD CLAMP NUT (2 REQ'D)

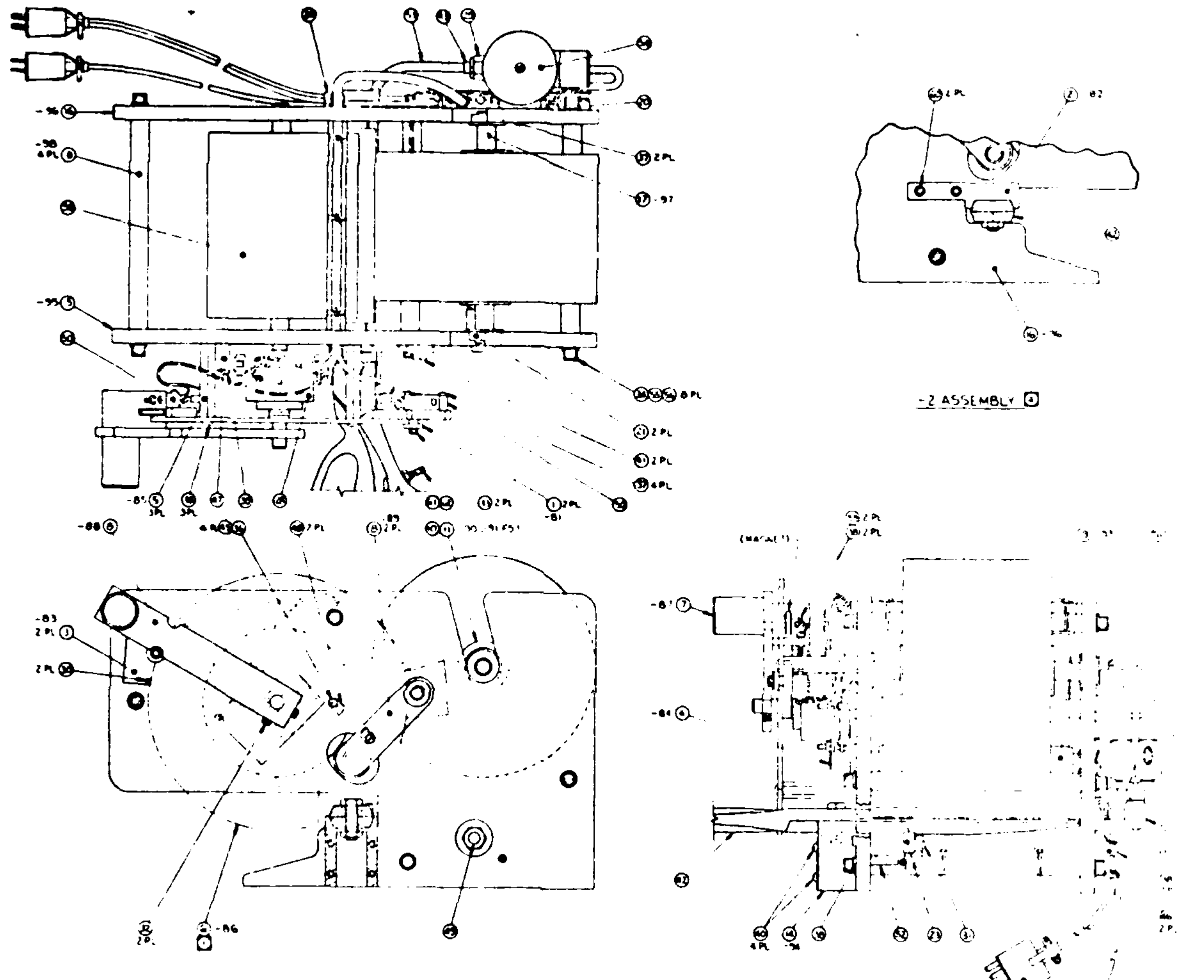


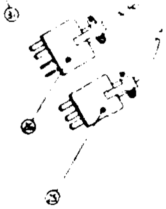
1. MATL ALUMINUM ALLOY, QQ-A-250/11, TEM T4

NOTES

APPENDIX I

FILM AND FOIL CUTTING APPARATUS



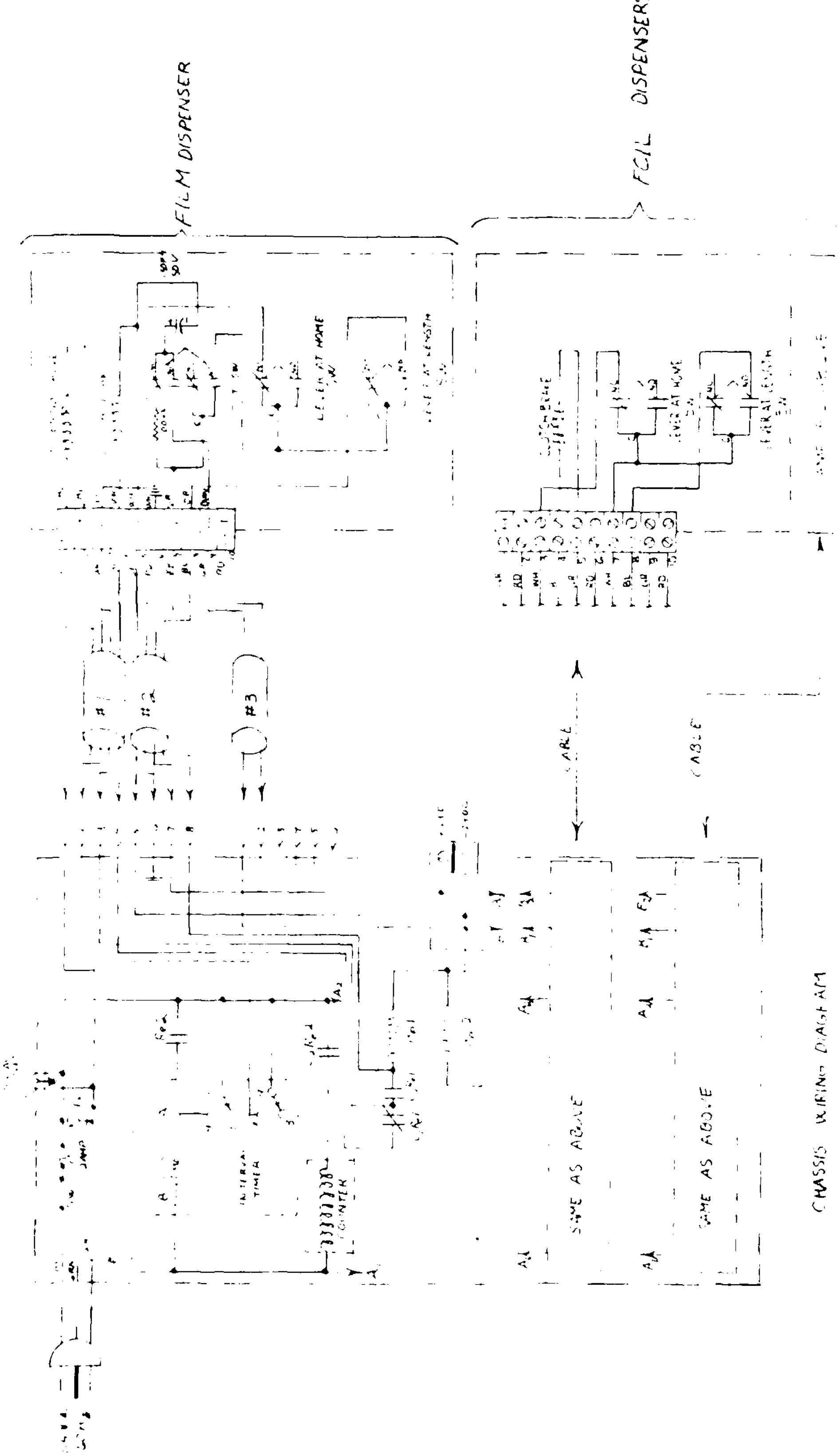


4 DASH 2 [illegible] CONFIGURATION IDENTICAL TO DASH 1 ASSEMBLY EXCEPT THE MOUNTING METHOD AND ORIENTATION OF SHEARS (ITEM 42)

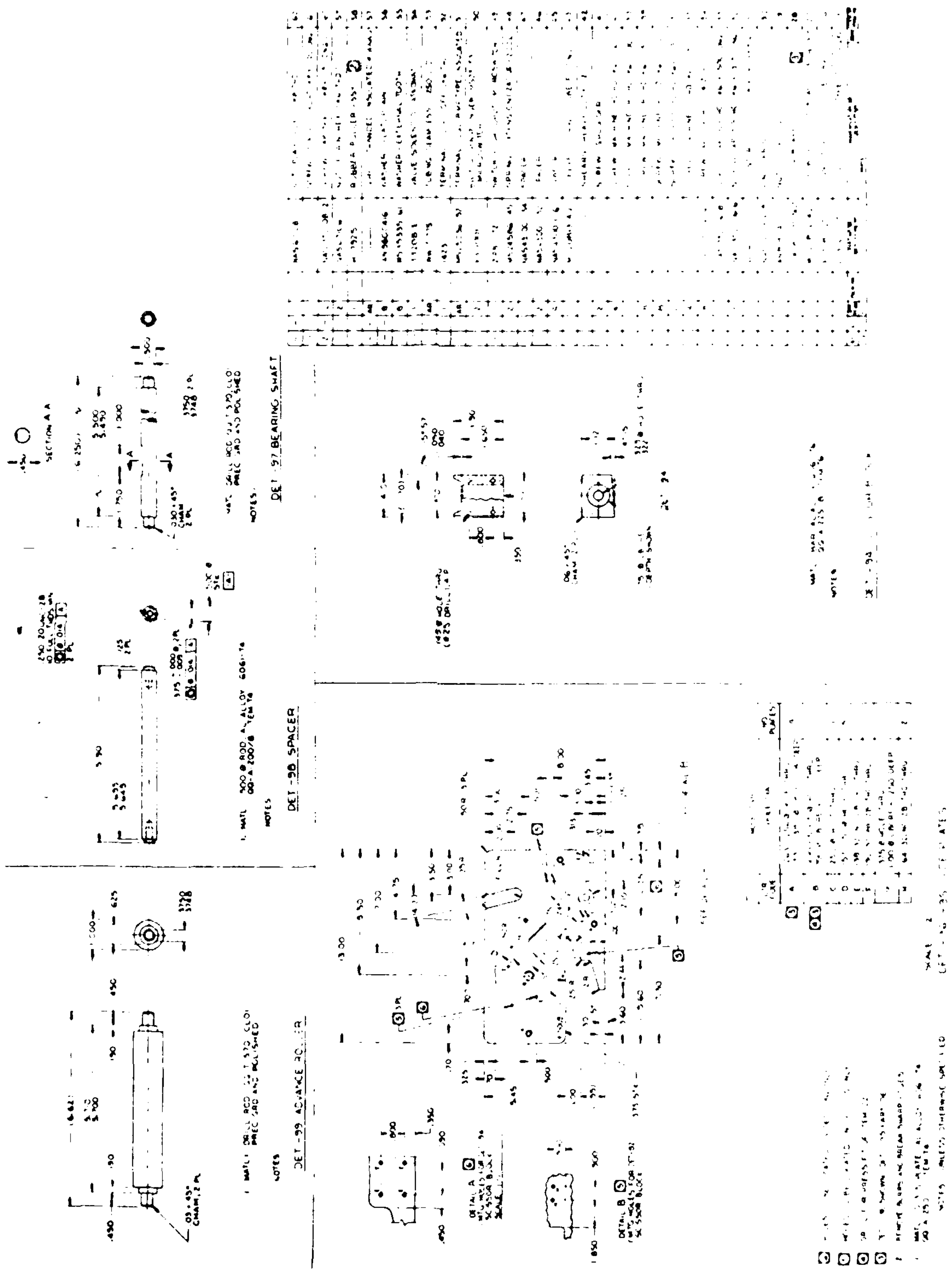
5 MUST BE PURCHASED FROM
[illegible] DYNAMICS INC
P.O. BOX [illegible]
[illegible] CONN 06022

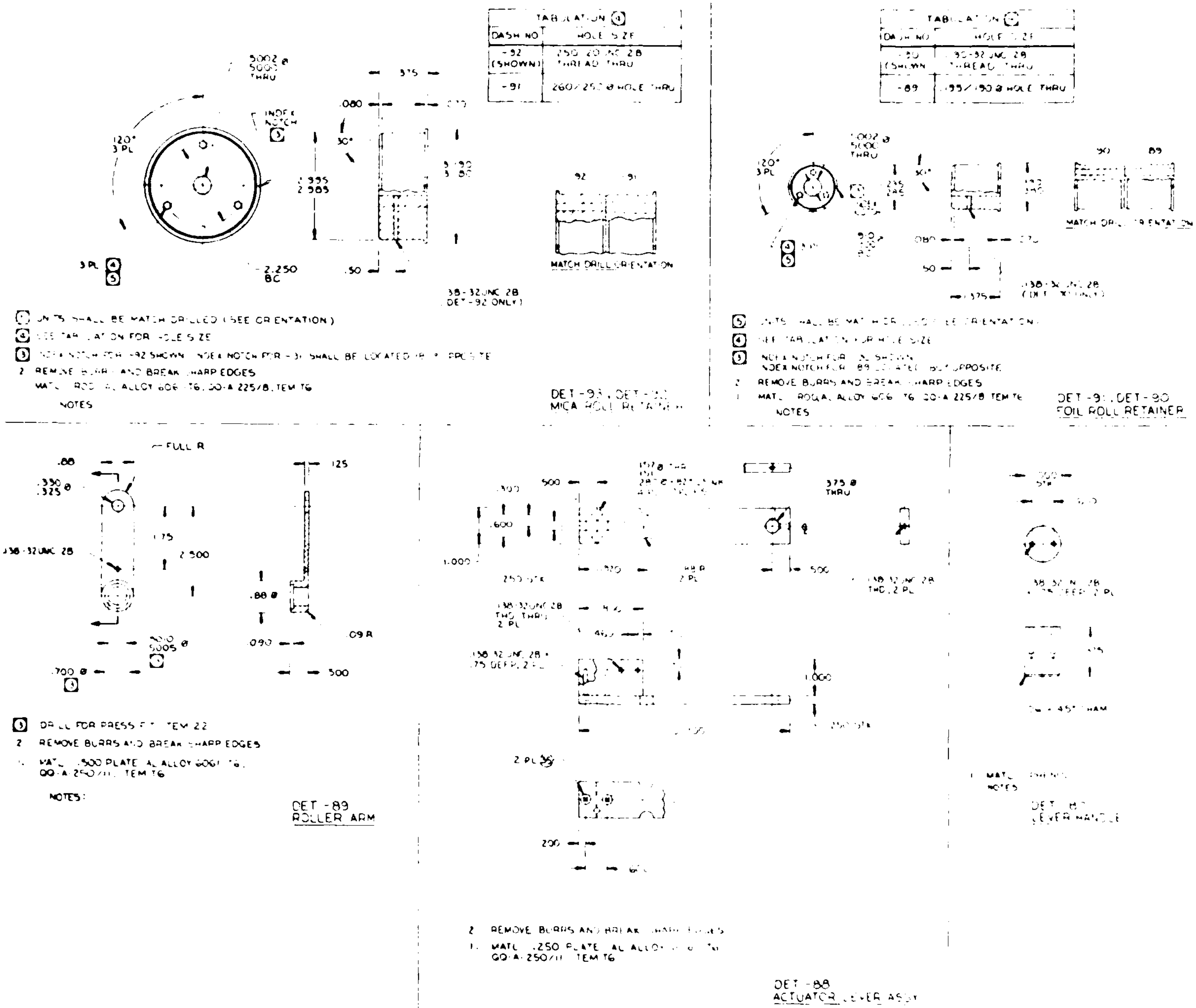
MAY BE PURCHASED FROM:
GLENN [illegible]
26 [illegible] AVE
ROSEMEAD, CA

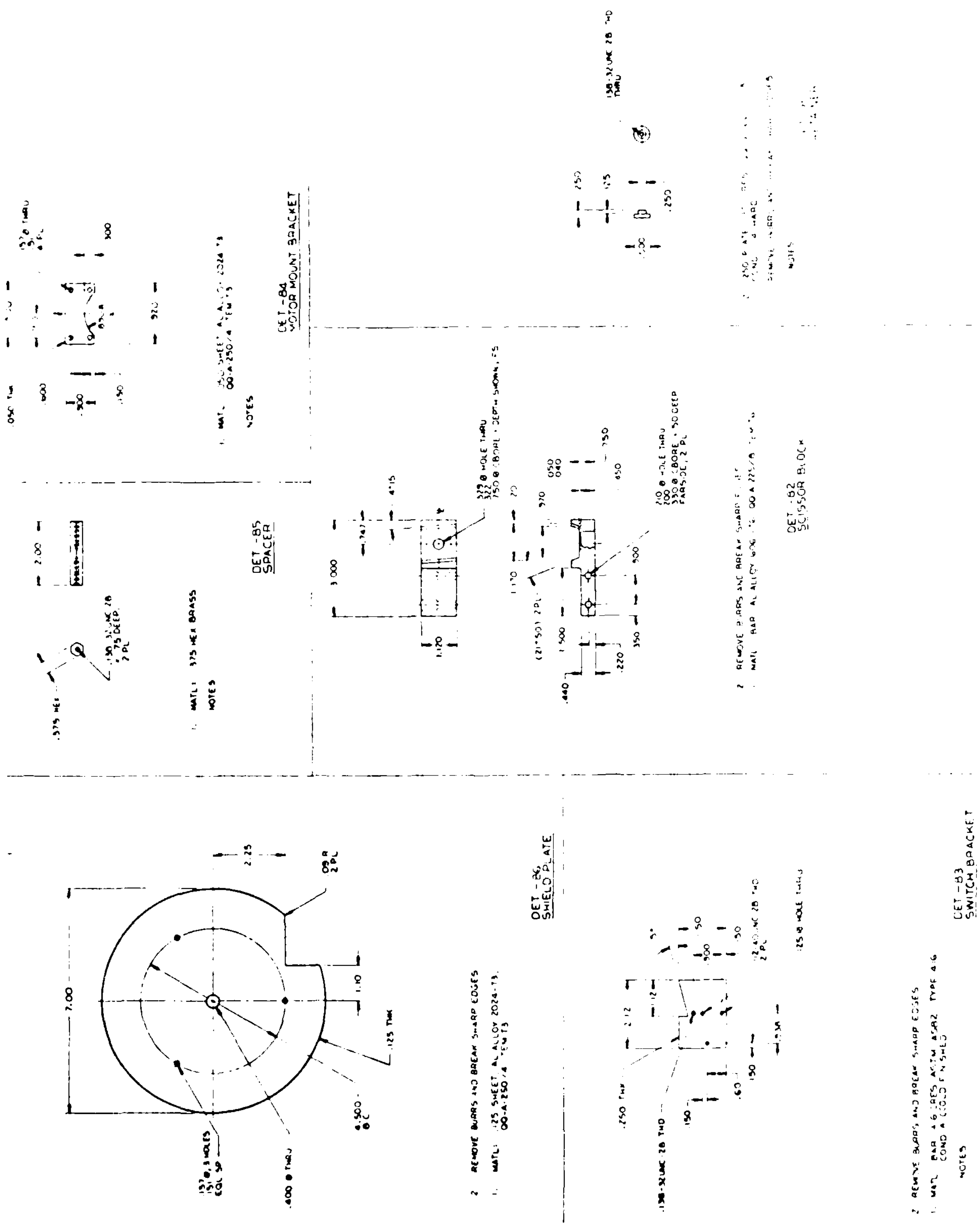
PARTS SHOWN IN PHANTOM LINES FOR CLARITY



CHASSIS WIRING DIAGRAM

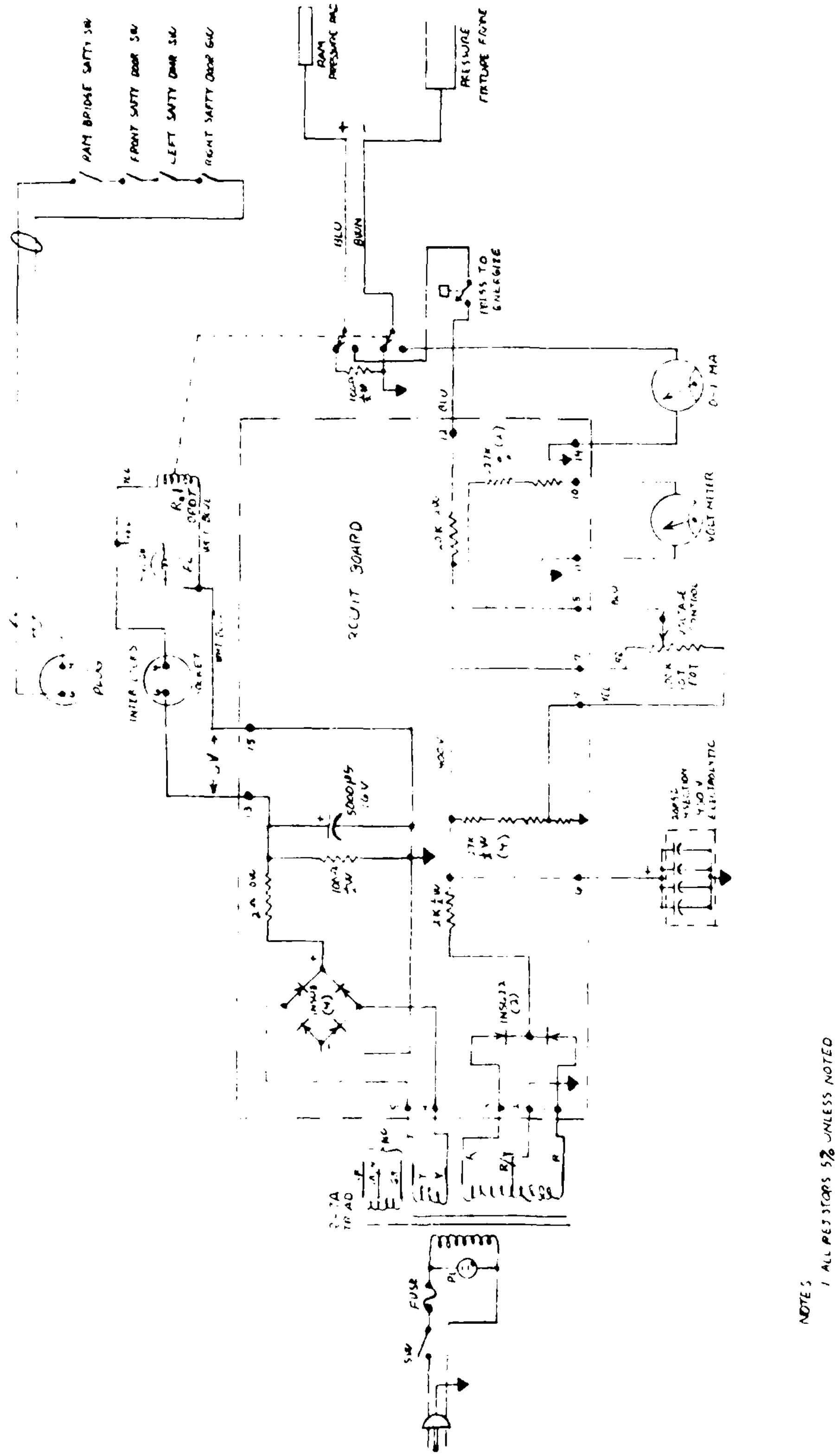

DET-97 BEARING SHAFT
DET-98 SPACER
DET-99 ADVANCE ROLLER


TABULATION 4
DASH NO | HOLE SIZE
-92 (SHOWN) | .250-20 UNC 2B THREAD THRU
-91 | .260/.250 Ø HOLE THRU
5.002 Ø 5.000 THRU
120° 3 PL
INDEX NOTCH 3
3 PL 4 5
2.250 BC
2.995 2.985
.080
30°
.375
.50
3.90 3.80
92
91
MATCH DRILL ORIENTATION
.38-32UNC 2B (DET-92 ONLY)
5 UNITS SHALL BE MATCH DRILLED (SEE ORIENTATION)
4 SEE TABULATION FOR HOLE SIZE
3 INDEX NOTCH FOR -92 SHOWN. INDEX NOTCH FOR -91 SHALL BE LOCATED 180° OPPOSITE
2 REMOVE BURRS AND BREAK SHARP EDGES
MATL ROD AL ALLOY 6061-T6, QQ-A-225/8, TEMP T6
NOTES
DET-93, DET-92
MICA ROLL RETAINER
TABULATION 4
DASH NO | HOLE SIZE
-90 (SHOWN) | .190-32 UNC 2B THREAD THRU
-89 | .195/.190 Ø HOLE THRU
1.002 Ø 1.000 THRU
120° 3 PL
30°
90
89
MATCH DRILL ORIENTATION
.080
.50
.375
.138-32 UNC 2B
5 UNITS SHALL BE MATCH DRILLED (SEE ORIENTATION)
4 SEE TABULATION FOR HOLE SIZE
3 INDEX NOTCH FOR -90 SHOWN. INDEX NOTCH FOR -89 LOCATED 180° OPPOSITE
2 REMOVE BURRS AND BREAK SHARP EDGES
1 MATL ROD AL ALLOY 6061-T6, QQ-A-225/8 TEMP T6
NOTES
DET-91, DET-90
FOIL ROLL RETAINER
FULL R
.88
.330 Ø .325
.138-32UNC 2B
.175
2.500
.125
.88 Ø
.090
.09 R
.500
.5010 .5005 Ø 3
.700 Ø 3
3 DRILL FOR PRESS FIT ITEM 22
2 REMOVE BURRS AND BREAK SHARP EDGES
1 MATL .500 PLATE AL ALLOY 6061-T6, QQ-A-250/11 TEMP T6
NOTES:
DET-89
ROLLER ARM
.500
.300
.600
1.000
.250 STK
.138-32UNC 2B THD THRU 2 PL
.138-32UNC 2B .75 DEEP, 2 PL
.375 Ø THRU
.500
.138-32UNC 2B THD, 2 PL
1.000
2 PL
.200
2 REMOVE BURRS AND BREAK SHARP EDGES
1 MATL .250 PLATE AL ALLOY 6061-T6, QQ-A-250/11 TEMP T6
DET-88
ACTUATOR LEVER ASSY
.38-32UNC 2B
1 MATL
NOTES
DET-87
LEVER HANDLE


DET - B4
MOTOR MOUNT BRACKET
DET - B5
SPACER
DET - B6
SHIELD PLATE
DET - B2
SCISSOR BLOCK
DET - B3
SWITCH BRACKET
REMOVE BURRS AND BREAK SHARP EDGES
NOTES

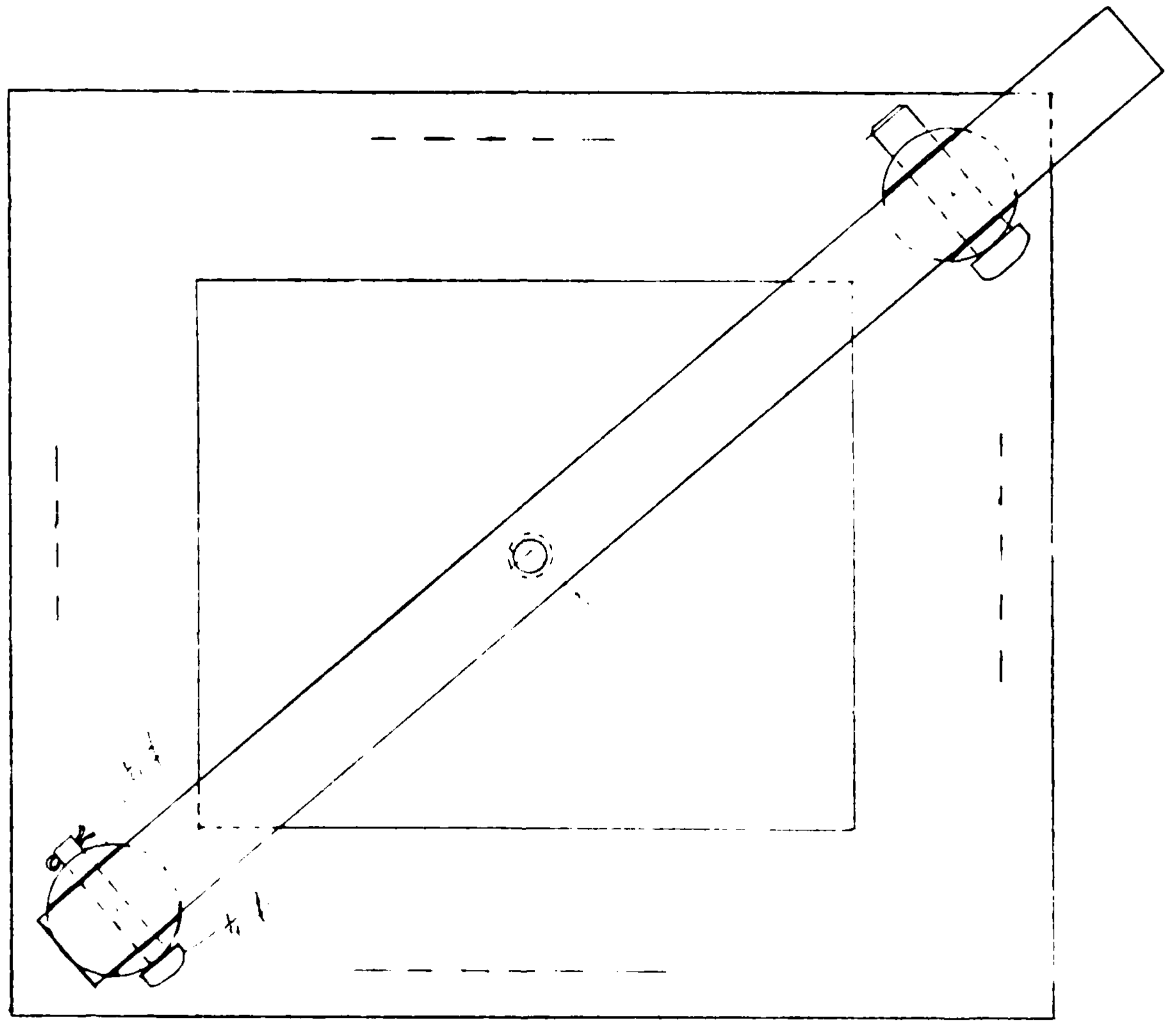
APPENDIX J

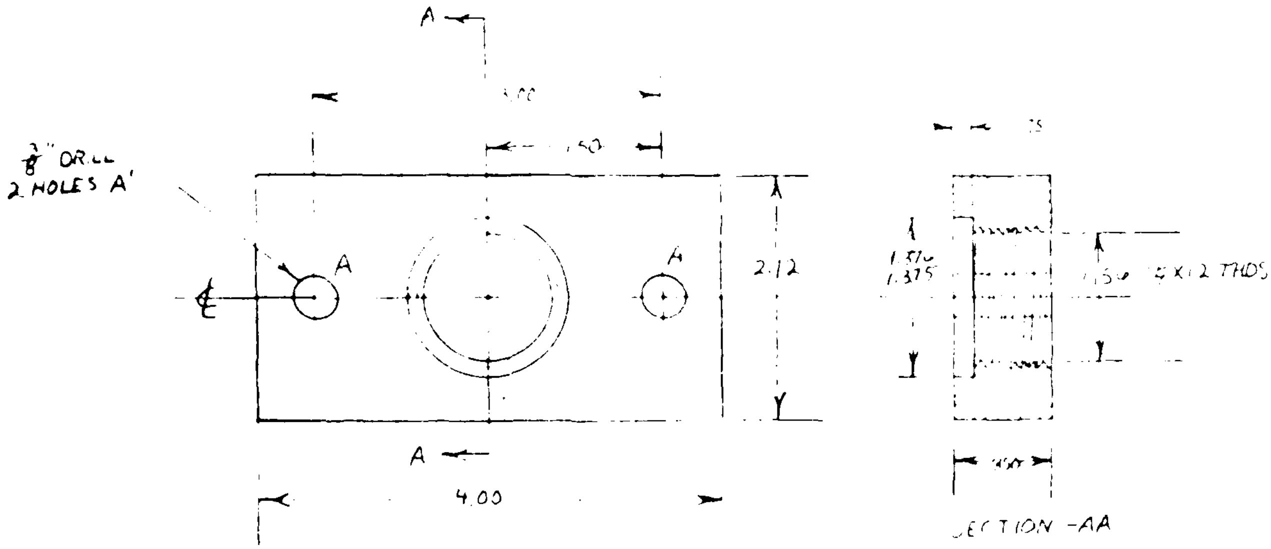
ADVANCED CAPACITOR VOLTAGE TEST POWER SUPPLY


RAM BRIDGE SAFETY SW
FRONT SAFETY DOOR SW
LEFT SAFETY DOOR SW
RIGHT SAFETY DOOR SW
PRESSURE FIXTURE FRAME
PRESS TO ENERGIZE
0-1 MA
VOLT METER
VOLTAGE CONTROL
FUSE
NOTES
1 ALL RESISTORS 5% UNLESS NOTED

APPENDIX K

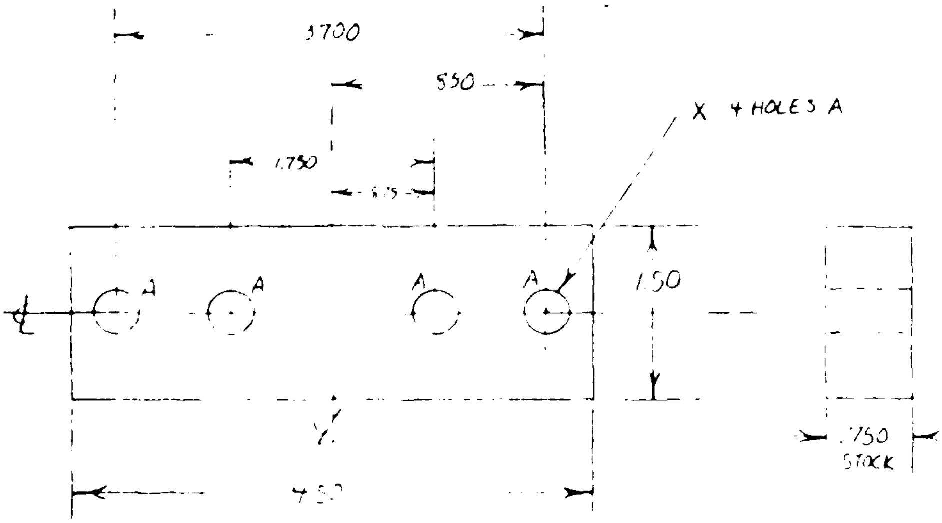
ADVANCED CAPACITOR VOLTAGE TEST FIXTURE





-82- NUT PLATE

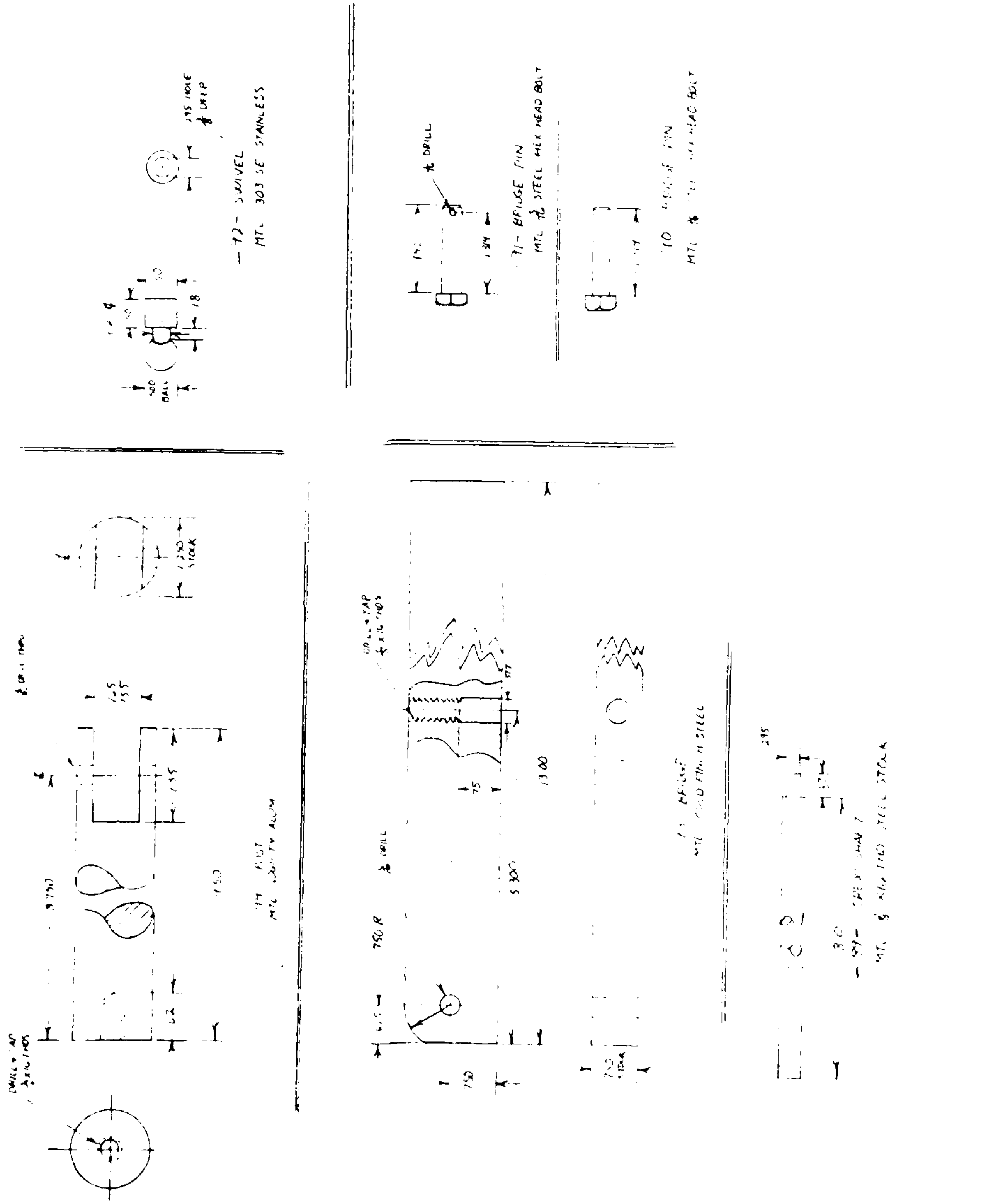
MTL 6061-T4 ALUM



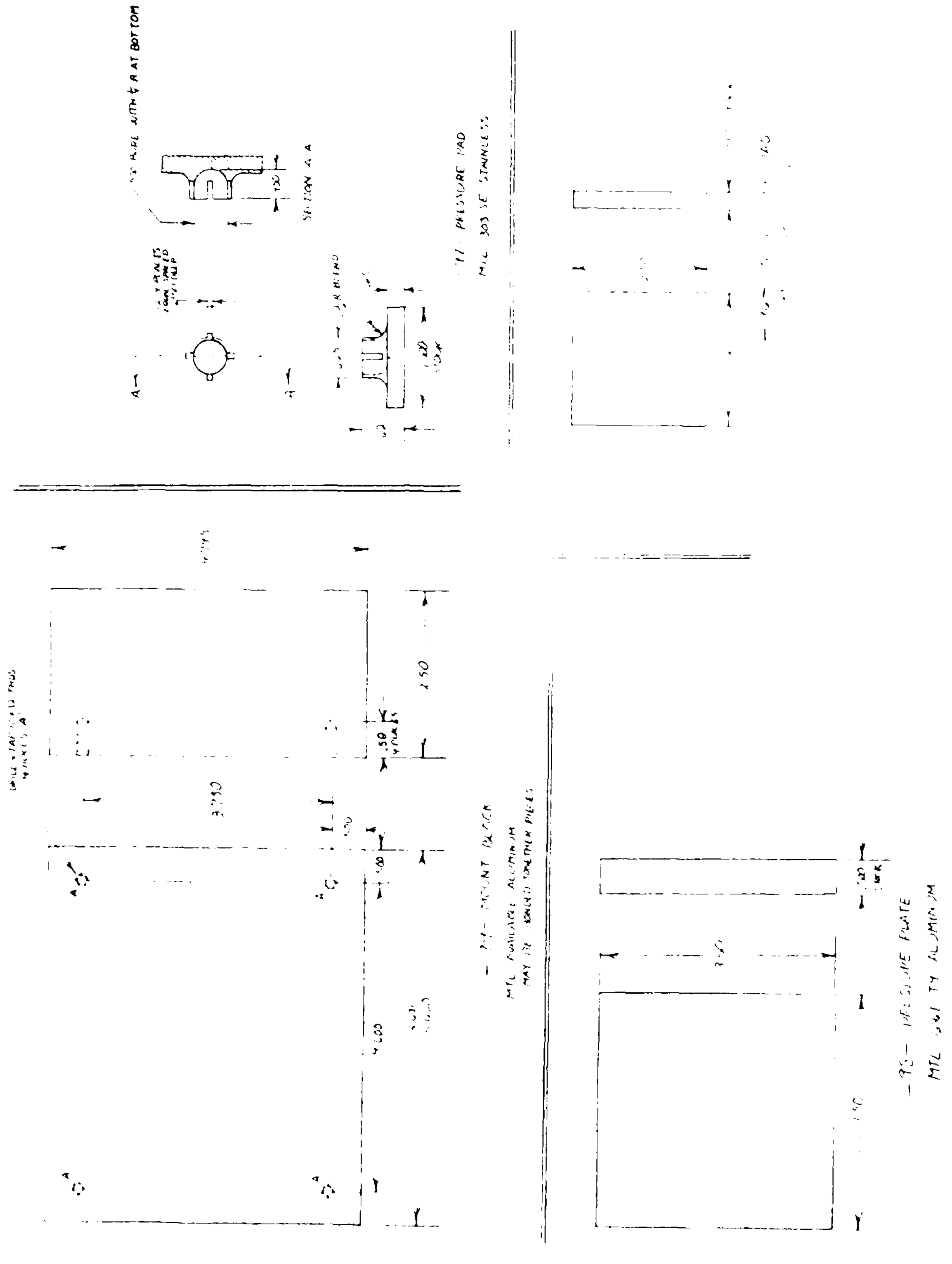
STIFFENER

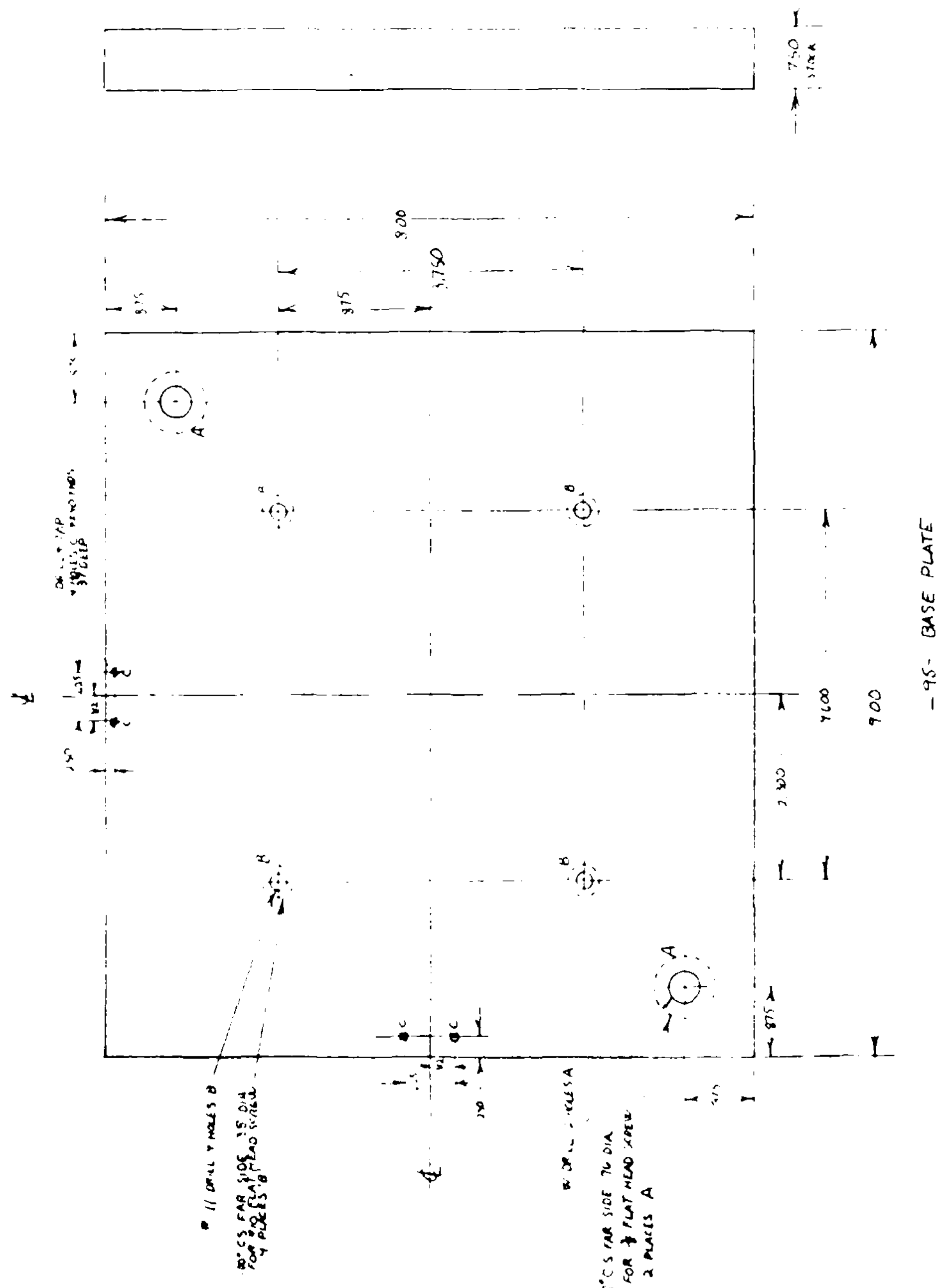
MTL 6061-T4 ALUM

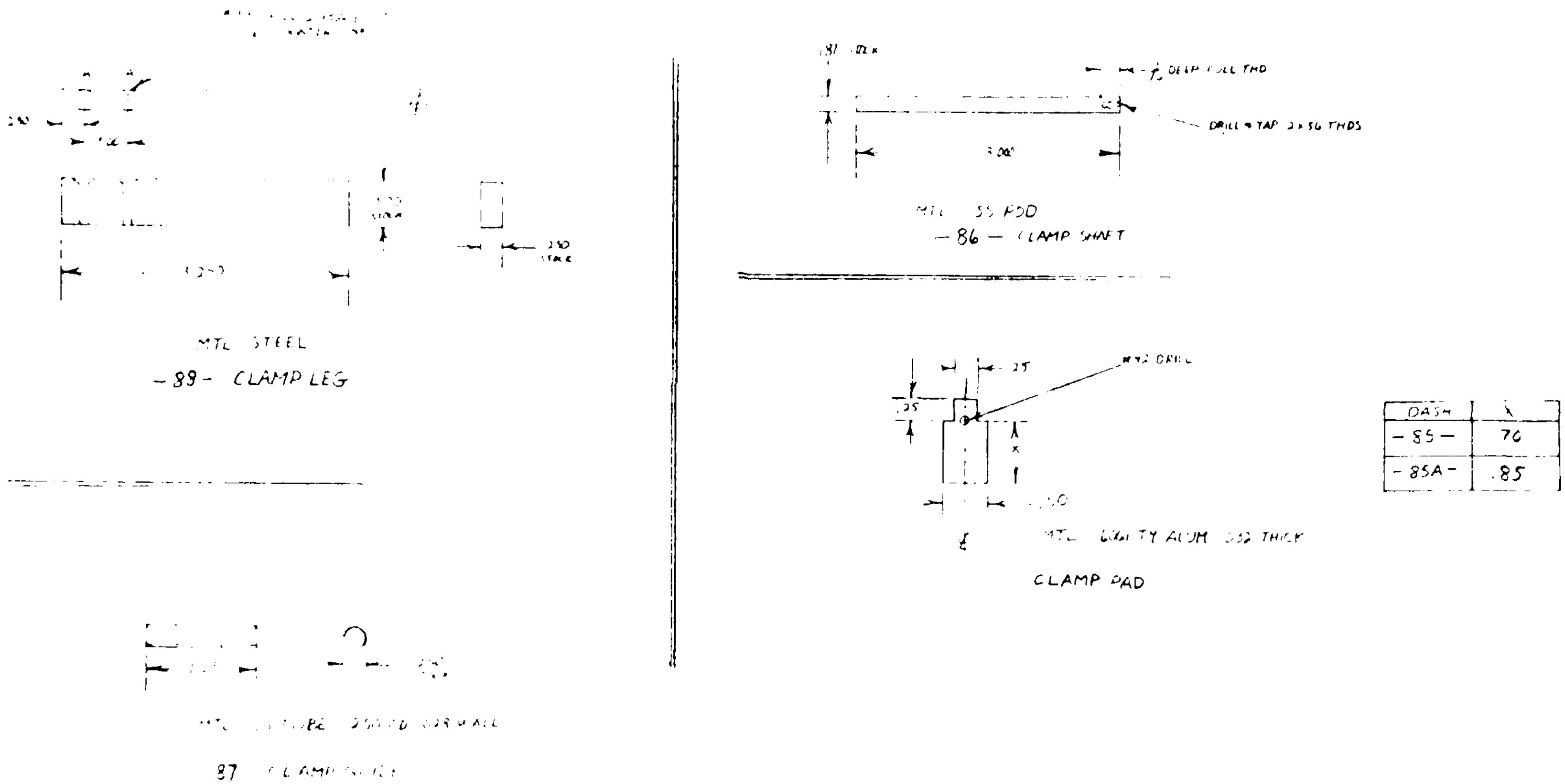
DASH	X
81	3/8 DRILL
80	DRILL + TAP 3/8x16 THD

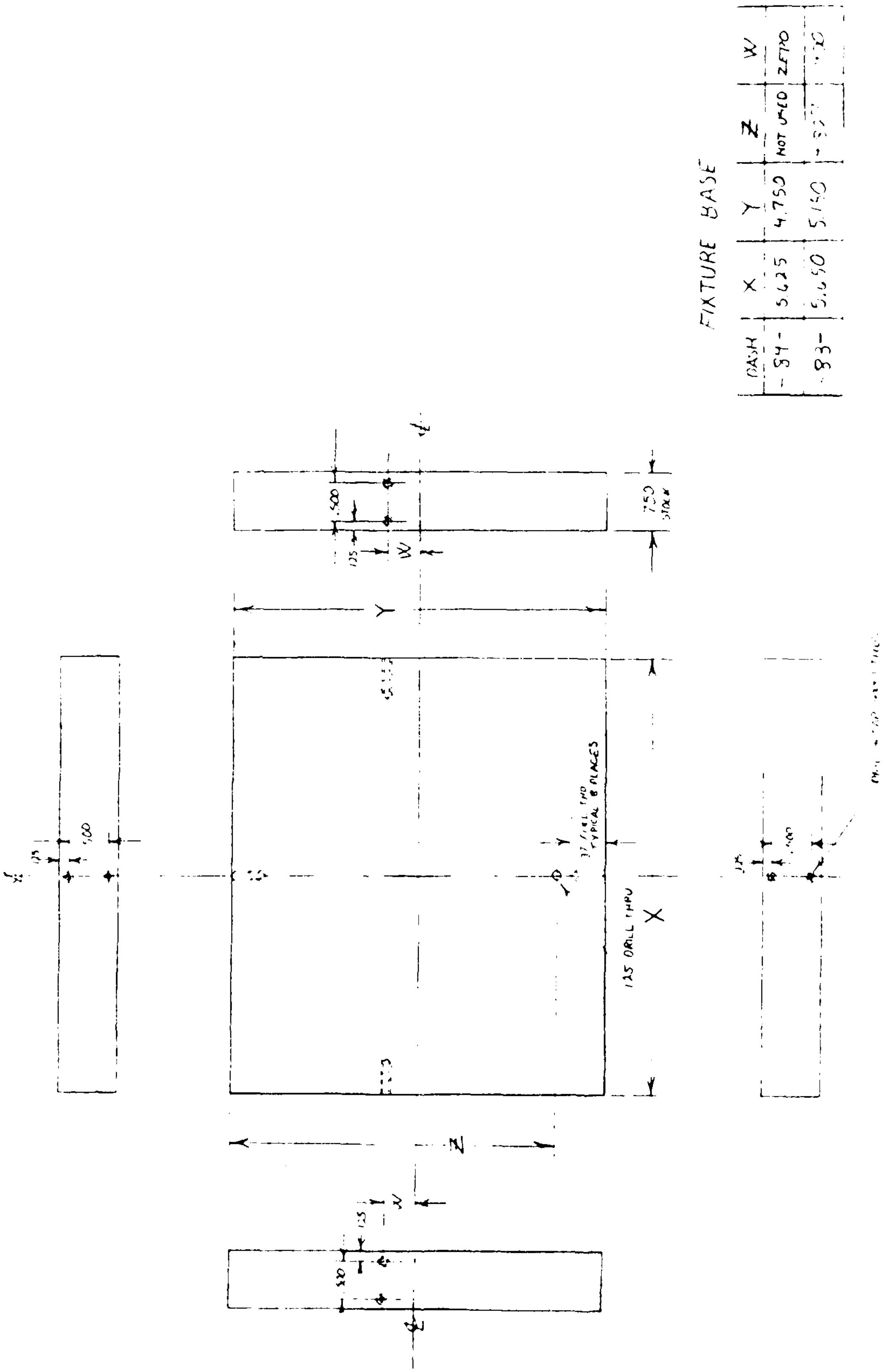


-72- SWIVEL
MTL 303 SE STAINLESS
71- BRIDGE PIN
MTL 3/16 STEEL HEX HEAD BOLT




-95- BASE PLATE
9.00
7.00
3.750
.875
2.300
2 PLACES A


MTL STEEL
-89- CLAMP LEG
-86- CLAMP SHAFT
DRILL & TAP
CLAMP PAD
DASH
-85-
.76
-85A-
.85
.25
87



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